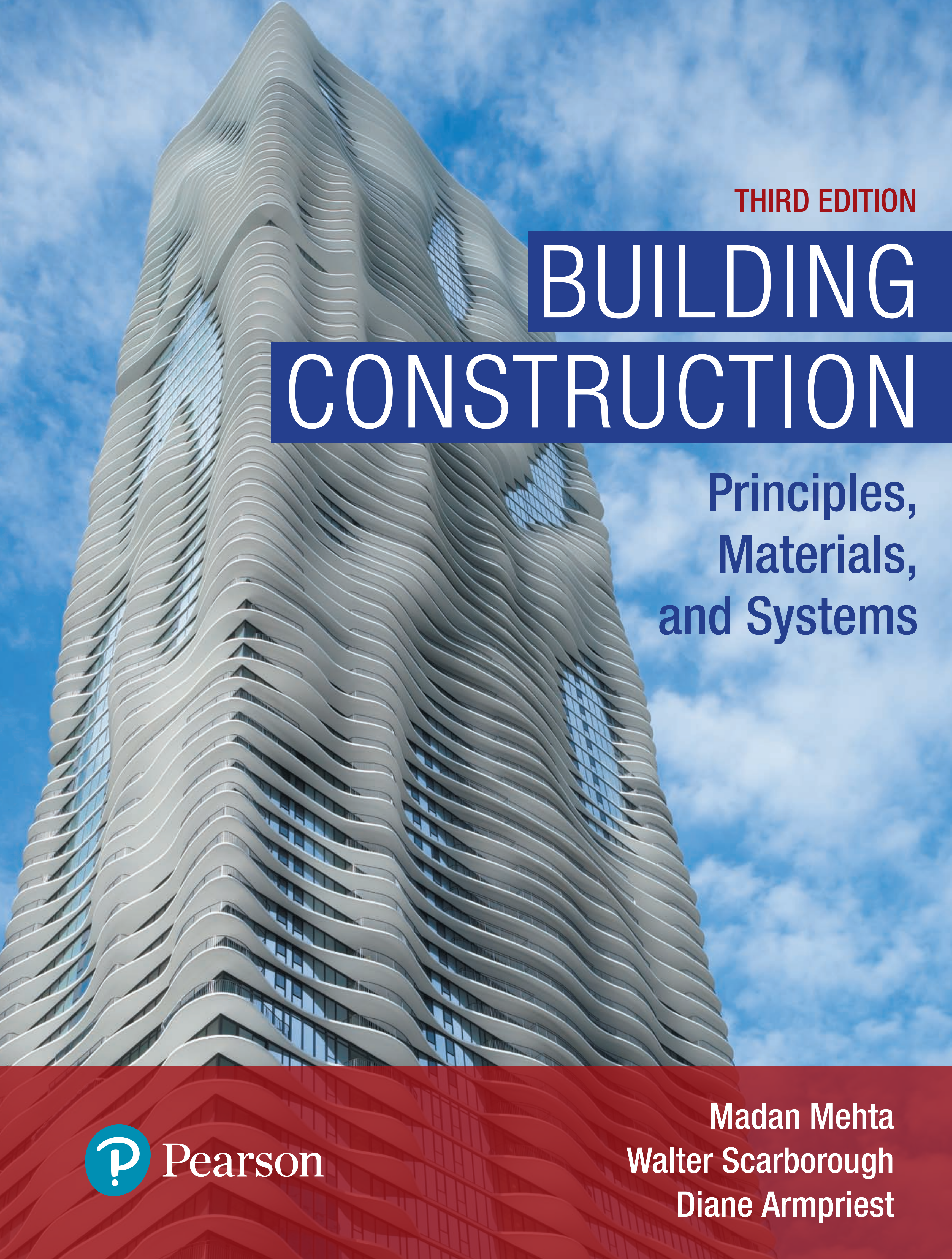

THIRD EDITION

BUILDING CONSTRUCTION

Principles, Materials, and Systems

Madan Mehta
Walter Scarborough
Diane Armpriest

Pearson

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Principles, Materials, and Systems

Third Edition

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PREFACE

The authors gratefully acknowledge the overwhelming response of the academic and professional communities of architecture, engineering, and construction to the first two editions of this text in recognition of its unique pedagogical philosophy and distinguishing features. We hope that this full-color third edition, which retains the book's uniqueness and includes several revisions to update it to the current state of professional practice, will continue to meet or exceed the expectations of the readers.

As stated in the preface to previous editions, building construction is a society's most dynamic enterprise, rooted in the inherent desire of humans to continually improve their habitat. The impact of this dynamism on building construction is that new products and construction systems are added to the existing stock in a never-ending process. In addition to new materials, new versions of traditional materials are proliferating. Consequently, today's designers and constructors face an unprecedented challenge as they strive to make well-informed decisions in the face of an expanding number of competing products and systems available for a given application.

The most accessible source of information on building products often comes from those who produce them. Although product testing is generally conducted by independent agencies, the results come to us through the filter of the manufacturers' vested interests and aggressive sales strategies, slanting the information unduly in favor of a specific product.

How do we, as designers and constructors, develop a critical faculty that enables us to sift facts from exaggeration and relevance from insignificance? How do we deal with the immense regional and international diversity of construction? How do we learn to function successfully in an increasingly litigious environment?

The core philosophy of this text is embedded in the belief that the best way for today's designers and constructors to respond successfully to the challenges just cited is for them to be sufficiently grounded in the principles and science of construction and the related systems. After all, the principles will be sustained, just as the conventional materials and practices will become dated all too soon. Equally important is the belief that architects, engineers and constructors, well versed in the principles governing the performance of materials and systems, can produce a more resilient and sustainable built environment.

PARTS 1 AND 2

The study of principles alone is not sufficient to master or fully grasp a subject. The principles must be illustrated by current and traditional practices in order to connect with the real-world design and construction. *Building Construction: Principles, Materials, and Systems* aims to do just that. Therefore, the text is divided into two parts:

- *Part 1*, consisting of 10 chapters, deals primarily with the principles of building materials' and building assemblies' performance.
- *Part 2*, consisting of 27 chapters, deals primarily with specific materials and assemblies.

The experience of the authors indicates that by introducing the basic principles common to the performance of most materials early in the course, it is possible to preclude or reduce repetition when progressing from one material or system to another. For example, thermal insulation is provided differently in different assemblies, but the thermal behavior of various assemblies is entrenched in the same basic principles. Similarly, all building assemblies must have some measure of fire endurance. Therefore, it makes sense to deal with the general properties and performance requirements of materials and systems in advance of their specifics.

However, there cannot be an absolute separation between the principles and their application. Some reiteration of the fundamentals as one proceeds through various materials and systems is unavoidable; in fact, it is pedagogically necessary. Additionally, there are certain principles that are limited only to one or two materials or assemblies. Those principles must be discussed in pertinent chapters.

DISTINGUISHING FEATURES

The book has several distinctive features. Each chapter is divided into convenient segments that pause with a set of multiple-choice (*Practice Quiz*) questions. Their purpose is to help the reader gain a broad understanding of the subject and assimilate its highlights. Answers to practice quizzes are provided in the end sheets of the book to facilitate self-testing by the readers. Testing for a detailed understanding and the ability to apply knowledge gained from a chapter is accomplished through *Review Questions* provided at the end of each chapter.

A large number of *Margin Notes* expand on critical topics or topics that would stimulate the reader to pursue additional self-directed inquiry. Where a critical topic needs expanded coverage, beyond that given in the main body of the chapter or in margin notes, it is provided in the *Expand Your Knowledge* sections. Almost every chapter has one or more such sections.

Several chapters conclude with a section titled *Principles in Practice*. These sections provide the opportunity for the interested reader (students, practicing architects, and engineers) to pursue in-depth study of the applications of construction principles to design issues without creating an undue burden in the main body of the chapter.

An entire chapter (Chapter 10) is devoted to the *Principles of Sustainable Construction* in Part 1 of the text and this is followed up with a special section in various chapters of Part 2 called *Focus on Sustainability*. *Appendix B: Preliminary Sizing of Structural Members*, which provides rules of thumb for determining the approximate dimensions of structural members of conventional wood, steel, masonry and concrete structures as one consolidated reference—a handy guide in design studios for students and practitioners.

As the reader will observe, the book is copiously illustrated. Two-dimensional and three-dimensional line art supplement the text descriptions. Color in line art has been used only in places where color improves dissemination of information.

Several architectural drawings and details have been retained in the original two-dimensional black-and-white format.

Photographs and photorealistic renderings are intended to simulate a live, real-world construction site experience for the reader. Because of the use of color, some photorealistic renderings in this book can be mistaken for photographs. A particularly distinctive feature of the book is that approximately 95% of its 600-plus photographs have been taken from various construction sites by the (primary) author in response to the demands of the text descriptions. Archival photos from manufacturers or industry sources have been kept to a minimum and carefully chosen to ensure relevance and their conformance with the best contemporary construction practices.

WHAT IS NEW IN THE THIRD EDITION

As previously mentioned, several revisions have been made in this edition while retaining the book's distinctiveness. Virtually every chapter has been revised to some degree. Chapters 1, 5, 6, 7, 10, 20, 33, and 36 have been completely revised with entirely new manuscripts. Chapters 2, 13, 15, 26, 28, 29, and 37 contain substantial manuscript revisions.

Various factors have contributed to revisions. Some of these are due to the continuous upgrading of our knowledge in the science and principles of materials and construction. Other revisions are the result of changes in means, methods, and the technologies related to construction, such as the widespread use of virtual construction. Some chapters have been reworked and provided with enhanced graphics to improve content accessibility. New products and assemblies that show promise of successful future applications have been added.

A major factor, however, that has prompted revisions in several chapters is the updates in codes and standards, particularly in the International Building Code (IBC), the International Energy Conservation Code (IECC), the International Green Construction Code (IGCC), and the United States Green Building Council's (USGBC) LEED rating system. Owing to their roots in the science of construction, the updates in these documents have led to revisions in both Part 1 and Part 2 chapters. For example, the new requirement in IECC to provide continuous envelope insulation is based on studies that testified to an unduly large reductions in insulation effectiveness caused by seemingly small thermal bridges. Consequently, the IECC update has led to revisions in Chapter 5 (Thermal Properties) and also in chapters that cover the detailing of wall cladding assembles (Chapters 27 through 29).

Similarly, the new version (version 4) of USGBC's LEED rating system has completely revised its Materials and Resources (MR) section. This change in the rating system is expected to contribute significantly to sustainability efforts as an increasingly large number of jurisdictions adopt the IGCC to ensure that the jurisdiction's entire building stock has some minimum level of sustainability. The default sustainability rating is set by several jurisdictions to correspond to a specified number of points in LEED rating system.

ACADEMIC PROGRAMS AND THIS TEXT

Building Construction: Principles, Materials, and Systems, a joint undertaking of two educators and one practitioner, has been written for use in programs in architecture, architectural engineering, construction science, and construction management. The size and extent of its coverage make it an ideal text for a two-semester course sequence. However, it can also be used successfully in other curricular contexts. It can be used in a one-semester introductory class to prepare beginning students for subsequent courses in structures and environmental controls, and it can be used later as a text in a more advanced construction course and as a design studio supplement.

LIMITATIONS

A cursory glimpse of the chapter titles of this text will reveal that building construction is a multidimensional discipline. To develop reasonable competence in this discipline, a fair knowledge of the fundamentals of design, history, art, and building science is necessary. This must be supplemented by careful and frequent observation of the construction process and interaction with contractors, material manufacturers, and assembly fabricators.

In other words, building construction cannot be learned merely by reading a book on the subject, regardless of the book's comprehensiveness. A book provides only the necessary introduction and the opportunities for the reader to explore and pursue the subject further. Although this book includes a large number of illustrations and construction photographs, they should not be regarded as a substitute for the reader's own observation of materials, details, and construction processes.

The book deals with the more commonly used, time-tested materials and assemblies. It does not pretend to cover some of the emerging technologies because of their uncertain future. An authentic test of a building assembly's performance must come from the field, because it is virtually impossible to simulate that in a laboratory.

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ANSWERS TO QUIZZES (INSIDE OF BACK COVER)

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CHAPTER 1

An Overview of the Building Delivery Process

(How Buildings Come into Being)

CHAPTER OUTLINE

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1.2 Predesign Phase

1.3 Design Phase

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Building construction is a complex, significant, and rewarding process. It begins with an idea and culminates in a structure that may serve its occupants for several decades, even centuries. Like the manufacturing of products, building construction requires an ordered and planned assembly of materials. It is, however, far more complicated than product manufacturing. Buildings are assembled outdoors by a large number of diverse constructors and artisans on all types of sites and are subject to all kinds of weather conditions.

Additionally, even a modest-sized building must satisfy many performance criteria and legal constraints, requires an immense variety of materials, and involves a large network of design and production firms. Building construction is further complicated by the fact that no two buildings are identical; each one must be custom built to serve a unique function and respond to its specific context and the preferences of its owner, user, and occupant.

Because of a building's uniqueness, we invoke first principles in each building project. Although it may seem that we are "reinventing the wheel", we are in fact refining and improving the building delivery process. In so doing, we bring to the task the collective wisdom of the architects, engineers, and contractors who have done so before us. Although there are movements that promote the development of standardized, mass-produced buildings, these seldom meet the distinct needs of each user.

Regardless of the uniqueness of each building project, the flow of activities, events, and processes necessary for a project's realization is virtually the same in all buildings. This chapter presents an overview of the activities, events, and processes that bring about a building—from the inception of an idea or a concept in the owner's mind to the completed design by the architects and engineers and, finally, to the actual construction of the building by the contractor.

Design and construction are two independent but related and generally sequential functions in the realization of a building. The former function deals with the creation of the documents, and the latter function involves interpreting and transforming these documents into reality—a building or a complex of buildings.

The chapter begins with a discussion of various stakeholders (personnel involved in the design and construction of the project) and the relational framework among them. Subsequently, a description of the two major elements of design documentation—construction drawings and specifications—is provided. Finally, the chapter examines some of the methods used for bringing a building into being, referred to as the *project delivery methods*. From the owner's perspective, these methods are called *project acquisition methods*.

The purpose of this chapter, as its title suggests, is to provide an overall, yet distilled, view of the construction process and its relationship with design. Although several contractual and legal issues are discussed, they should be treated as introductory. A reader requiring additional information on these topics should refer to texts specially devoted to them.

1.1 PROJECT DELIVERY PHASES

The process by which a building project is delivered to its owner may be divided into the following five phases, referred to as the *project delivery phases*. Although there is usually some overlap between adjacent phases, they generally follow this order:

- Predesign phase
- Design phase
- Preconstruction phase
- Construction phase
- Postconstruction phase

1.2 PREDESIGN PHASE

During the predesign phase (also called the *planning* or *programming phase*), the project is defined in terms of its function, purpose, scope, size, and economics. This is the most crucial of the five phases, and is almost always managed by the owner and the owner's team. The success or failure of the project may depend on how well this phase is defined, detailed, and managed. Obviously, the clearer the project's definition is, the easier it is to proceed to the subsequent phases. Some of the important predesign tasks are:

- Details of the project's program.
- Economic feasibility assessment, including the project's overall budget and financing.
- Site assessment and selection, including the verification of the site's appropriateness, and determining its designated land use (see Chapter 2).
- Governmental constraints assessment, for example, building code and zoning constraints (see Chapter 2) and other legal aspects of the project.
- Sustainability rating—whether the owner would like the project to achieve sustainability rating, such as the U.S. Green Building Council's (USGBC's) Leadership in Energy and Environmental Design (LEED) certification at some level (see Chapter 10).
- Design team selection.

BUILDING (PROJECT) PROGRAM

This includes defining the activities, functions, and spaces required in the building, along with their approximate sizes and their relationships with each other. For a house or another small project, the program is usually simple and can be developed by the owner without external assistance. For a large project, however, where the owner may be an institution (such as a corporation, school board, hospital, religious organization, or governmental entity), developing the program may be a complex exercise. This may be due to the size and complexity of the project or the need to involve several individuals—a corporation's board of directors, for example—in decision making. These constituencies may have different views of the project, making it difficult to create a consensus.

Program development may also be complicated by situations in which the owner has a fuzzy idea of the project and is unable to define it clearly. By contrast, experienced owners tend to have a clear understanding of the project and generally provide a detailed, unambiguous program to the architect.

Although the owner must provide the program details to the architect, it is not unusual for the owner to involve the architect in preparing the program for some architecturally complex projects. In this instance, the architect may be hired early during the predesign phase. Note that the architect's role in the preparation of the building program is not considered a part of the architect's "basic" services, but as an "additional" service, compensated separately [Ref. 1.1].

Whatever the situation, preparing the program is the first step in the project delivery process. It should be spelled out in writing and in sufficient detail to guide the design, reduce the liability risk for the architect, and avoid its misinterpretation. If a revision is made during the progress of the project, the owner's written approval is necessary.

NOTE

Building (Project) Program

The American Institute of Architects (AIA) Document B141-1997, *Standard Form of Agreement Between Owner and Architect*, defines the building program: "A program is a written statement setting forth design objectives, constraints, and criteria for a project . . . . A program includes space requirements and relationships, flexibility and expandability, special equipment and systems, and site requirements. If a comprehensive program is not available at the outset of the project, the owner may obtain the architect's assistance in developing one as an expansion of services".

1.3 DESIGN PHASE

The design phase begins after the selection of the architect. Because the architect (usually a firm) may have limited capabilities for handling the broad range of building-design activities, several different, more specialized consultants are usually required, depending on the size and scope of the project.

In most projects, the design team consists of the architect, landscape architect, civil and structural consultants, and mechanical, electrical, and plumbing (MEP) consultants. In complex projects, the design team may also include an acoustical consultant, roofing and waterproofing consultant, cost consultant, building code consultant, signage consultant, interior designer, and so on.

Some design firms have an entire design team (architects and specialized consultants) on staff, in which case, the owner will contract with a single firm. Generally, however, the design team comprises several different design firms. In such cases, the owner typically contracts the architect, who in turn contracts the remaining design team members, Figure 1.1.

Thus, the architect functions as the prime design professional and, to a limited degree, as the owner's representative. The architect is liable to the owner for his or her own work and that of the consultants. For that reason, most architects ensure that their consultants carry adequate liability insurance.

ARCHITECT'S LIABILITY FOR WORK DONE BY OWNER-CONTRACTED CONSULTANT

In some projects, the owner may contract some consultants directly, particularly a civil consultant (for a survey of the site, site grading, slope stabilization, and the design of site drainage system), a geotechnical consultant (for investigation of the soil properties), and a landscape architect (for landscape and site design), Figure 1.2. These consultants may be engaged before or at the same time as the architect.

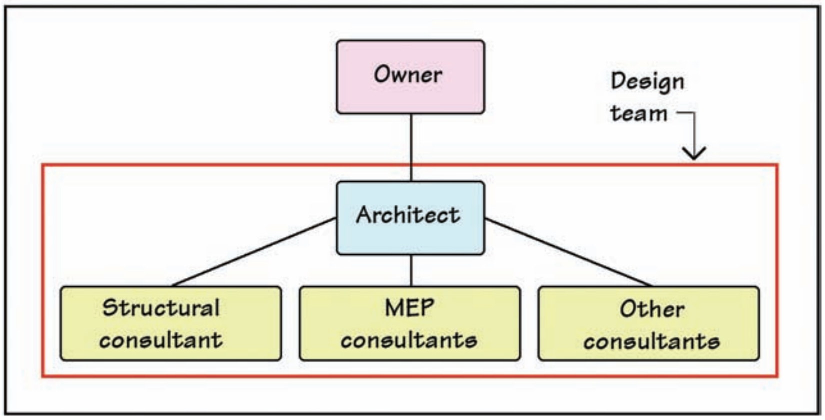


FIGURE 1.1 Members of a typical design team, and their interrelationships with each other and the owner in a traditional contractual set-up. A line in this illustration indicates a contractual relationship between parties. ("MEP consultants" is an acronym for mechanical, electrical, and plumbing consultants.)

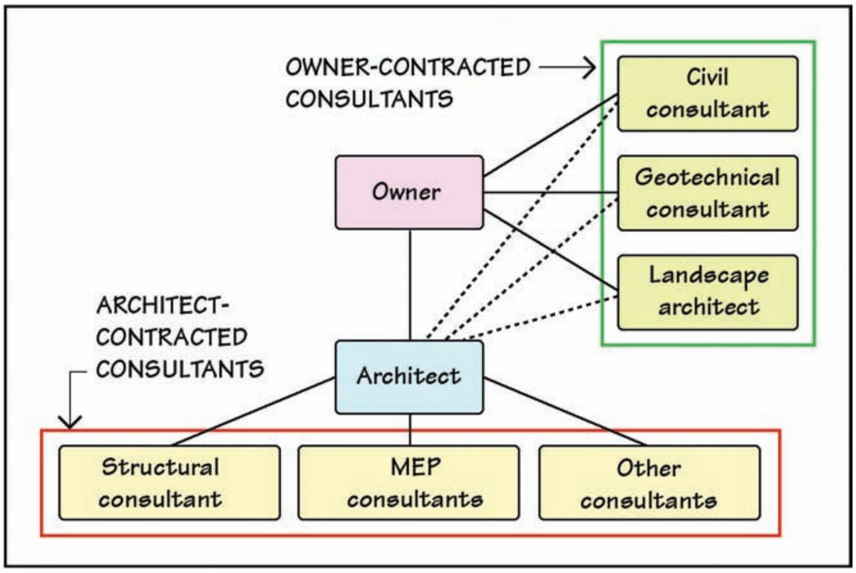

OWNER-CONTRACTED CONSULTANTS
Civil consultant
Geotechnical consultant
Landscape architect
Owner
ARCHITECT-CONTRACTED CONSULTANTS
Architect
Structural consultant
MEP consultants
Other consultants

FIGURE 1.2 Members of a typical design team, and their interrelationships with each other and the owner in a project where some consultants are contracted directly by the owner. A solid line in this illustration indicates a contractual relationship between parties. A dashed line indicates a communication link, not a contract.

Even when a consultant is contracted directly by the owner, the architect retains some liability for the consultant's work. This liability occurs because the architect, being the prime design professional, coordinates the entire design effort, and the consultants' work is influenced a great deal by the architectural decisions. Therefore, the working relationship between the architect and an owner-contracted consultant remains essentially the same as if the consultant were chosen by the architect.

ENGINEER AS PRIME DESIGN PROFESSIONAL

In some cases, an engineer or another professional may coordinate the design process. This generally occurs where architectural design is a minor component of a large-scale project. For example, in a highly technical project such as a power plant, an electrical engineer may be the prime design professional.

1.4 THREE SEQUENTIAL STAGES IN DESIGN PHASE

In most building projects, the design phase consists of three stages, which occur in the following sequence:

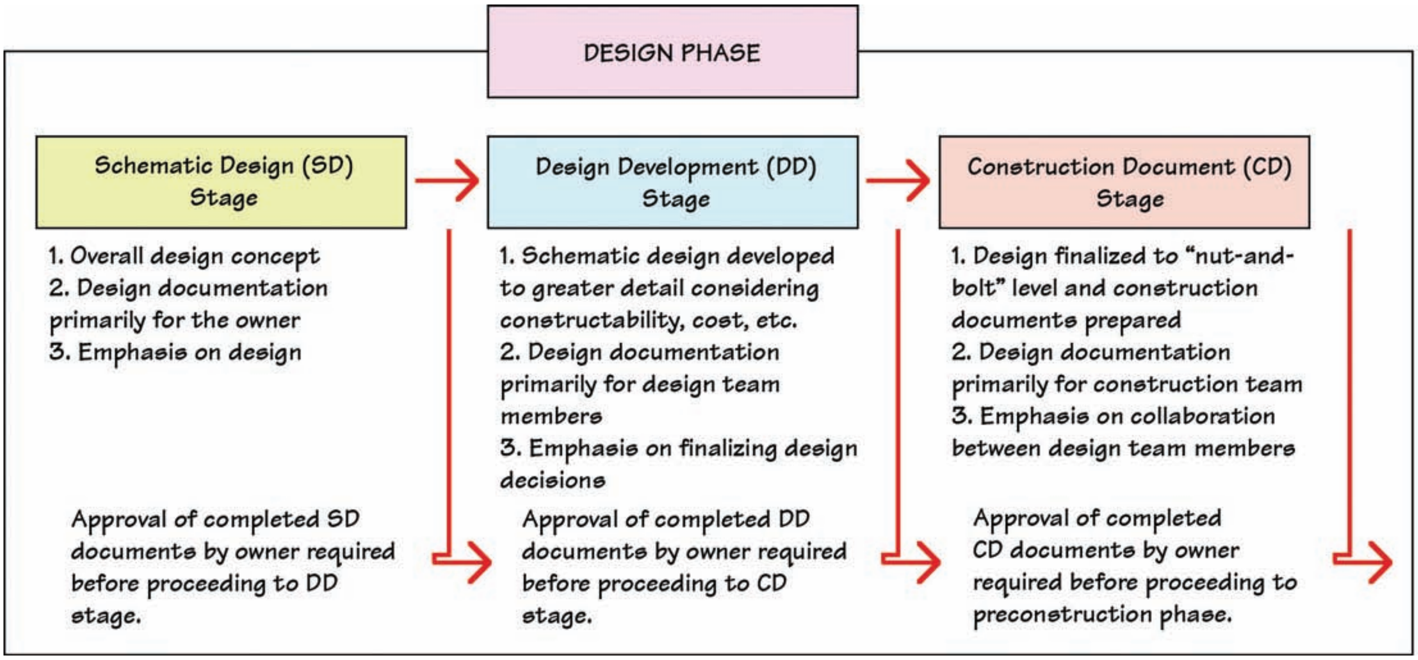

DESIGN PHASE
Schematic Design (SD) Stage
1. Overall design concept
2. Design documentation primarily for the owner
3. Emphasis on design
Approval of completed SD documents by owner required before proceeding to DD stage.
Design Development (DD) Stage
1. Schematic design developed to greater detail considering constructability, cost, etc.
2. Design documentation primarily for design team members
3. Emphasis on finalizing design decisions
Approval of completed DD documents by owner required before proceeding to CD stage.
Construction Document (CD) Stage
1. Design finalized to "nut-and-bolt" level and construction documents prepared
2. Design documentation primarily for construction team
3. Emphasis on collaboration between design team members
Approval of completed CD documents by owner required before proceeding to preconstruction phase.

FIGURE 1.3 Three sequential stages (steps) of the design phase and the important tasks accomplished in each stage.

- Schematic design (SD) stage
- Design development (DD) stage
- Construction document (CD) stage

Figure 1.3 illustrates the sequence and the important tasks accomplished in each stage. Note that at the end of each stage, a written approval from the owner is required before proceeding to the next stage, or from the design phase to the preconstruction phase.

SCHEMATIC DESIGN STAGE—EMPHASIS ON DESIGN

The schematic design gives graphic shape to the project program. It is an overall concept that illustrates key ideas of the design solution. The major player in this stage is the architect, who develops the design scheme (or several design options), generally with limited help from the consultants. Because most projects have strict budgetary limitations, a rough estimate of the project's probable cost is generally produced at this stage.

The schematic design usually goes through several revisions, because the first design scheme prepared by the architect will rarely be approved by the owner. The architect communicates the design proposal(s) to the owner through various types of drawings—plans, elevations, sections, freehand sketches, and three-dimensional graphics (isometrics, axonometrics, and perspectives). For some projects, a three-dimensional scale model of the entire building or the complex of buildings, showing the context (neighboring buildings) within which the project is sited, may be needed.

With significant developments in electronic media technology, especially building information modeling (BIM), computer-generated imagery has become common in architecture and related engineering disciplines. Computer-generated walk-through and flyover simulations are becoming increasingly popular for communicating the architect's design intent to the owner at the SD stage.

It is important to note that the schematic design drawings, images, models, and simulations, regardless of how well they are produced, are not adequate to construct the building. Their objective is merely to communicate the design scheme to the owner (and to consultants, who may or may not be on board at this stage), not to the contractor.

DESIGN DEVELOPMENT STAGE—EMPHASIS ON DECISION MAKING

Once the schematic design is approved by the owner, the process of designing the building in greater detail begins. During this stage, the schematic design is developed further—hence the term *design development* (DD) stage.

While the emphasis in the SD stage is on the creative, conceptual, and innovative aspects of design, the DD stage focuses on developing practical, pragmatic, and constructible solutions for the exterior envelope, structure, fenestration, interior systems, MEP systems, and so forth. This development involves strategic consultations with all members of the design team.

Therefore, the most critical feature of the DD stage is decision making, which ranges from broad design aspects to finer details. At this stage, the vast majority of decisions about products, materials, and equipment are made. Efficient execution of the construction documents depends directly on how well the DD is managed. A more detailed version of the specifications and probable cost of the project is also prepared at this stage.

CONSTRUCTION DOCUMENTS STAGE—EMPHASIS ON DOCUMENTATION

The purpose of the *construction documents* (CD) stage is to prepare all documents required by the contractor to construct the building. During this stage, the consultants and architect collaborate intensively to work out the "nuts and bolts" of the building and develop the required documentation, referred to as *construction documents*. All of the consultants advise the architect, but they also collaborate with each other (generally through the architect) so that the work of one consultant agrees with that of the others.

The construction documents consist of the following items:

- Construction drawings
- Specifications

CONSTRUCTION DRAWINGS

During the CD stage, the architect and consultants prepare their own sets of drawings, referred to as *construction drawings*. Thus, a project has architectural construction drawings, civil and structural construction drawings, MEP construction drawings, landscape construction drawings, and so on.

NOTE

Working Drawings and Construction Drawings

The term working drawings was used until the end of the twentieth century for what are now commonly referred to as *construction drawings*.

Construction drawings are dimensioned drawings (usually computer generated) that fully delineate the building. They consist of floor plans, elevations, sections, schedules, and various large-scale details. The details depict a small portion of the building that cannot be adequately described on smaller-scale plans, elevations, or sections.

Construction drawings are the drawings that the construction team uses to build the building. Therefore, they must indicate the geometry, layout, dimensions, types of materials, details of assembling the components, colors and textures, and so on. Construction drawings are generally two-dimensional drawings, but three-dimensional isometrics are sometimes used for complex details. Construction drawings are also used by the contractor to prepare a detailed cost estimate of the project at the time of bidding.

Construction drawings are not a sequence of assembly instructions, such as for a bicycle. Instead, they indicate what every component is and where it will be located when the building is completed. In other words, the design team decides the "what" and "where" of the building. The "how" and "when" (means, methods, and sequencing) of construction are entirely in the contractor's domain.

SPECIFICATIONS

Buildings cannot be constructed from drawings alone, because there is a great deal of information that cannot be included in the drawings. For instance, the drawings will give the locations of columns, their dimensions, and the material used (such as reinforced concrete), but the quality of materials, their properties (the strength of concrete, for example), and the test methods required to confirm compliance cannot be furnished on the drawings. This information is included in the document called *specifications*.

Specifications are written technical descriptions of the design intent, whereas the drawings provide the graphic description. The two components of the construction documents—the specifications and the construction drawings—complement each other and generally deal with different aspects of the project. Because they are complementary, they are supposed to be used in conjunction with each other. There is no order of precedence between the construction drawings and the specifications. Thus, if an item is described in only one place—either the specification or the drawings—it is part of the project, as if described in the other.

For instance, if the construction drawings do not show the door hardware (hinges, locks, handles, and other components) but the hardware is described in the specifications, the owner will get the doors with the stated hardware. If the drawings had precedence over the specifications, the owner would receive doors without hinges and handles.

Generally, there is little overlap between the drawings and the specifications. More importantly, there should be no conflict between them. If a conflict between the two documents is identified, the contractor must bring it to the attention of the architect promptly. In fact, construction contracts generally require that before starting any portion of the project, the contractor must carefully study and compare the drawings and the specifications and report inconsistencies to the architect.

If the conflict between the specifications and the construction drawings goes unnoticed initially but later results in a dispute, the courts have in most cases resolved it in favor of the specifications—implying that the specifications, not the drawings, govern the project. However, if the owner or the design team wishes to reverse the order, it can be so stated in the owner-contractor agreement.

EXPAND YOUR KNOWLEDGE

Relationship Between Construction Drawings and Specifications

Construction Drawings	Specifications
Design intent represented graphically	Design intent represented with words
Product/material may be shown many times	Product/material described only once
Product/material shown generically	Product/material identified specifically, sometimes proprietary to a manufacturer
Quantity indicated	Quality indicated
Location of elements established	Installation requirements of elements established
Size, shape, and relationship of building elements provided	Description, properties, characteristics, and finishes of building elements provided

THE CONSTRUCTION DOCUMENT SET

Just as the construction drawings are prepared separately by the architect and each consultant for their respective portions of the work, so are the specifications. The specifications from various design team members are assembled by the architect in a single document. Because the specifications are in text format (not as drawings), they are bound in book format. A few other items are also included in this document at a later stage, and the entire bound document is called the *project manual*, described in Section 1.7. The construction drawings plus the specifications constitute the construction document set, Figure 1.4 (see also Figure 1.11). Although hardcopy drawings and specification are common, their digital versions are being increasingly used.

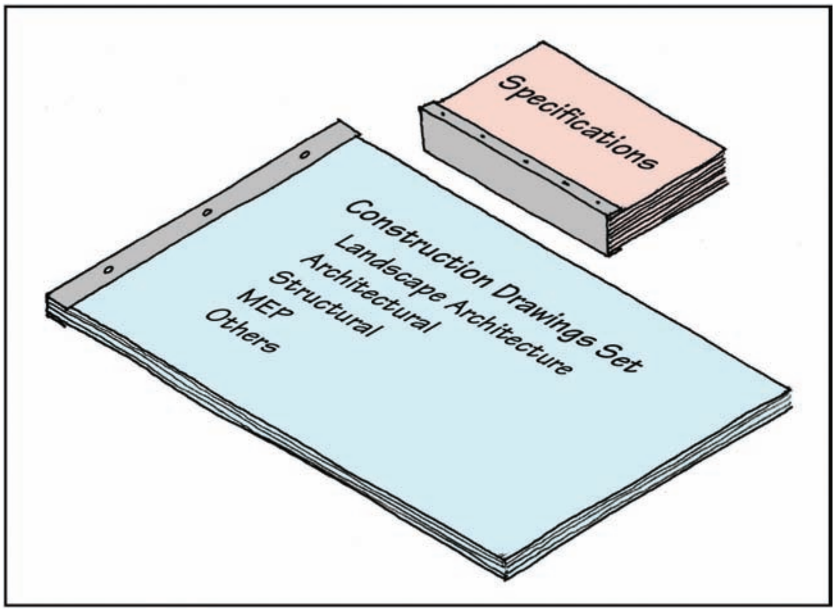


FIGURE 1.4 A construction document set consists of a set of architectural and consultants' construction drawings plus the specifications prepared by the architect and the consultants. The specifications are bound in book format along with other items.

OWNER'S ROLE DURING DESIGN PHASE

The owner's role in the design phase of the project may not appear as active as in the predesign phase, but it is important all the same. In fact, a conscientious owner will be fully involved throughout the entire project delivery process—from the predesign phase through the project closeout phase.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The delivery of a typical building project, as described in this text, may be divided into
   - **a.** two phases.
   - **b.** three phases.
   - **c.** four phases.
   - **d.** five phases.
   - **e.** six phases.
2. Establishing the project's economic feasibility and its overall budget is part of the design phase of the project.
   - **a.** True
   - **b.** False
3. The term MEP is an acronym for
   - **a.** municipal emergency plan.
   - **b.** mechanical, electrical, and plumbing.
   - **c.** mechanical, electrical, and piping.
   - **d.** mechanical and electrical plans.
   - **e.** mechanical and electrical plant.
4. The program for a building project is prepared by the
   - **a.** owner.
   - **b.** general contractor.
   - **c.** building official of the city.
   - **d.** architect.
   - **e.** all of the above collectively.
5. In a typical building project, the coordination of the building's design is done by the
   - **a.** owner.
   - **b.** general contractor.
   - **c.** building official of the city.
   - **d.** architect.
   - **e.** any one of the above, depending on the type of building.
6. The construction drawings of a building project are prepared during the
   - **a.** SD stage of the project.
   - **b.** DD stage of the project.
   - **c.** CD stage of the project.
   - **d.** preconstruction phase of the project.
   - **e.** construction phase of the project.
7. The construction drawings of a building project are drawings that the architect uses to explain the design to the owner.
   - **a.** True
   - **b.** False
8. The construction drawings of a building project are generally in the form of
   - **a.** freehand sketches.
   - **b.** two-dimensional plans, elevations, sections, and details.
   - **c.** three-dimensional drawings.
   - **d.** photographs of three-dimensional scale model(s).
   - **e.** all of the above.
9. The construction drawings for a building project generally consist of
   - **a.** architectural drawings and structural drawings.
   - **b.** architectural drawings, structural drawings, and MEP drawings.
   - **c.** architectural drawings, structural drawings, MEP, and QSA drawings.
   - **d.** architectural drawings, structural drawings, and QSA drawings.
   - **e.** none of the above.
10. The construction document set consists of
    - **a.** construction drawings.
    - **b.** construction drawings and construction schedule.
    - **c.** construction drawings, construction schedule, and owner-contractor agreement.
    - **d.** construction drawings, construction schedule, and specifications.
    - **e.** construction drawings and specifications.
11. The specifications of a typical building project are prepared by the
    - **a.** architect.
    - **b.** architect in collaboration with the GC.
    - **c.** architect in collaboration with the GC and the architect's consultants.
    - **d.** architect and the architect's consultants.
    - **e.** none of the above.

1.5 CSI MASTERFORMAT AND SPECIFICATIONS

The specification document for even a modest-sized project can run into hundreds of pages. It is used not only by the contractor and the subcontractors, but also by the owner, the material suppliers, and in fact, the entire construction team. With so many different people using it, it is necessary that the specifications be organized in a standard format so that each user can go to the section of particular interest without having to wade through the entire document.

The standard organizational format for specifications, referred to as *MasterFormat*, has been developed by the Construction Specifications Institute (CSI) and is the format most commonly used in the United States and Canada. MasterFormat is divided into two groups—(i) *Procurement and Contracting Requirements* group and (ii) *Specifications* group, Figure 1.5. The Specifications group is further divided into five subgroups, and each subgroup consists of divisions. The subgroup *General Requirements* comprises one division; *Facilities Construction* subgroup has 18 divisions; and the following three subgroups have 10 divisions each.

The total number of divisions in MasterFormat is 50, which are identified using six-digit numbers. The first two digits of the numbering system (referred to as *Level 1* digits) identify the division number. The 50 division numbers are 00, 01, 02, 03, . . . , 48, and 49. A division identifies the broadest collection of related products and assemblies, such as Division 03—Concrete.

The next two digits of the numbering system (*Level 2* digits) refer to various sections within the division, and the last two digits (*Level 3* digits) refer to the subsections within a section. In other words, Level 2 and Level 3 digits classify products and assemblies into progressively closer affiliations. Thus, Level 1 digits in MasterFormat may be compared to chapter numbers in a book, Level 2 digits to section numbers of a chapter, and Level 3 digits to subsection numbers of a section.

A complete list of MasterFormat titles is voluminous. Figure 1.6 provides a bird's-eye view of MasterFormat, showing groups, subgroups, and divisions in each subgroup. It also provides additional details of one of the divisions, Division 04—Masonry—as brief illustration of the numbering system. Note that the *Procurement and Contracting Requirements* group is Division 00 and the *Specifications* group consists of Divisions 01 to 49.

Also note that MasterFormat deals with all types of construction (new buildings, renovations, and maintenance). Construction work and products, not directly related with buildings (services, urban infrastructural construction, equipment, etc.) are also included—in Divisions 30 to 49.

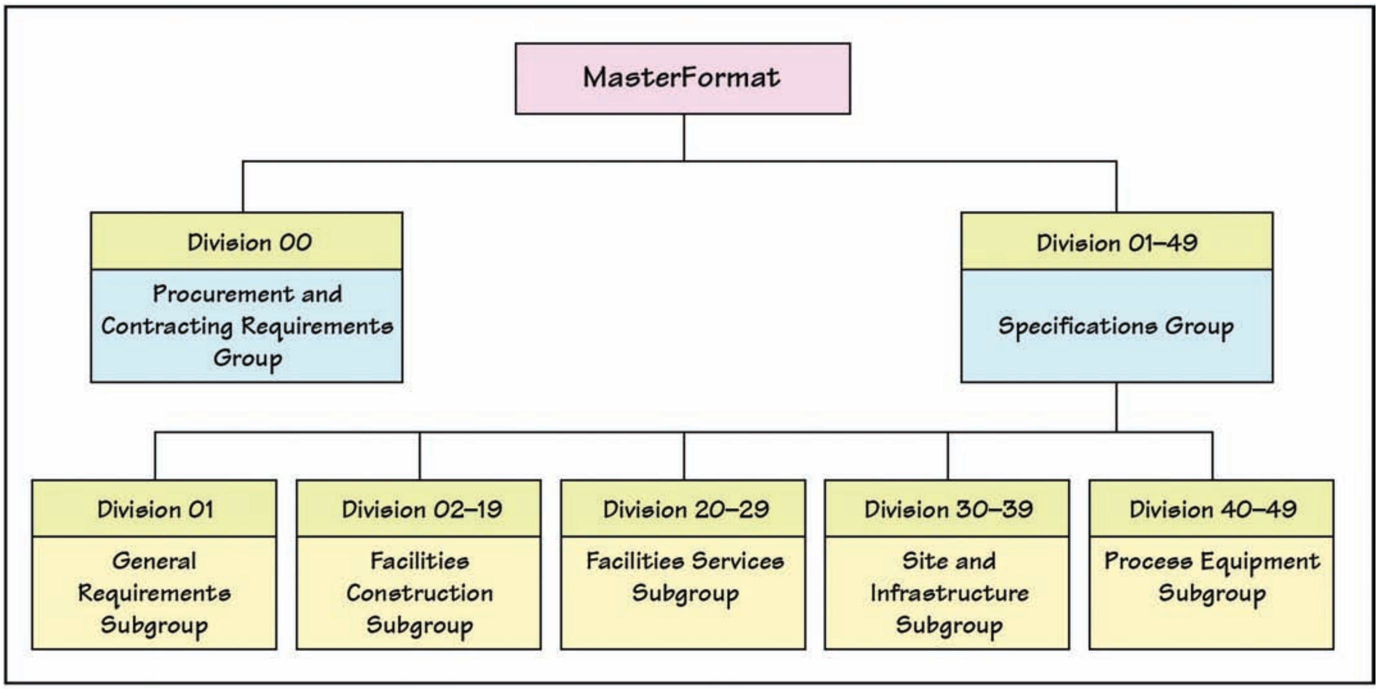
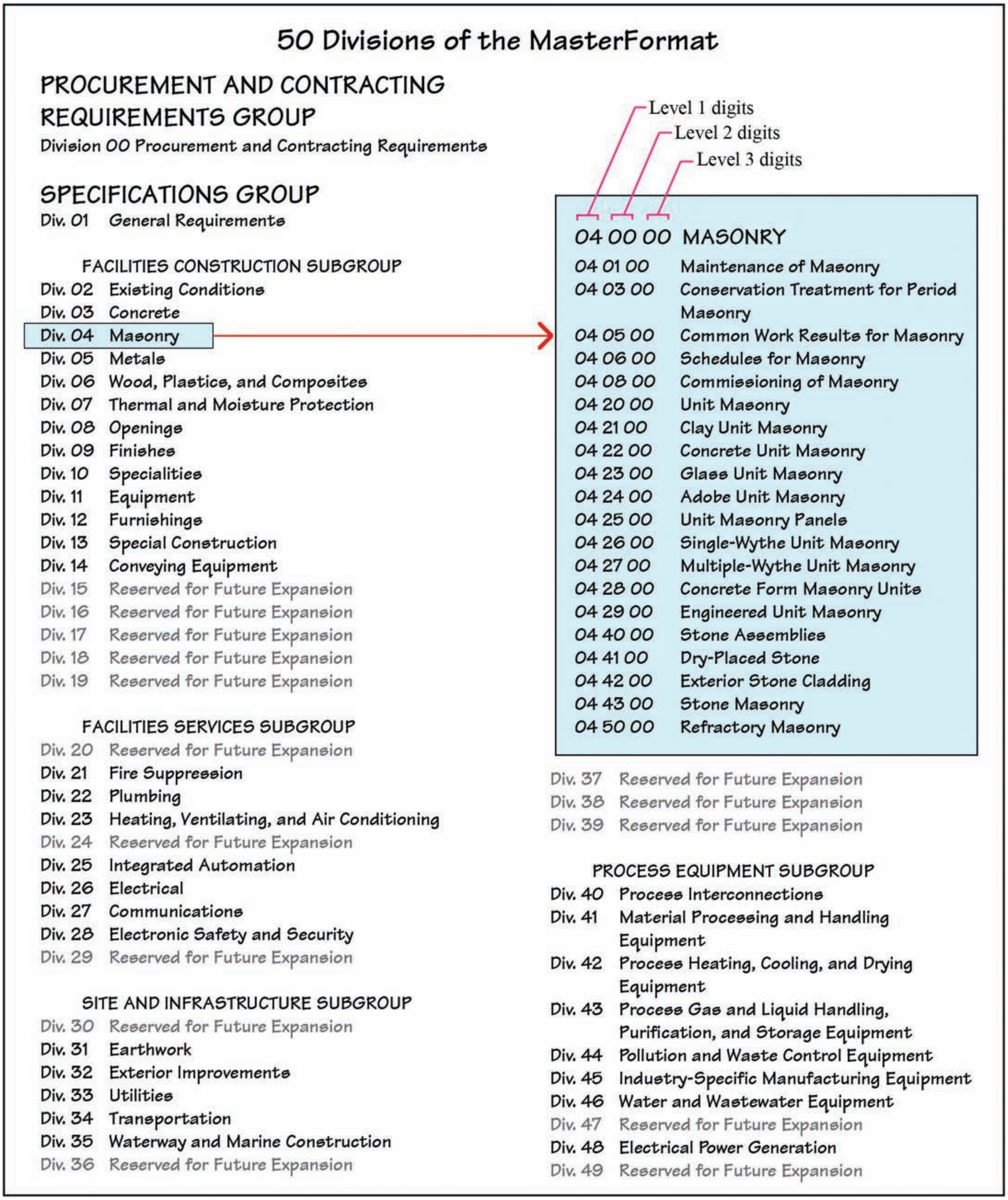

MasterFormat
Division 00
Procurement and Contracting Requirements Group
Division 01–49
Specifications Group
Division 01
General Requirements Subgroup
Division 02–19
Facilities Construction Subgroup
Division 20–29
Facilities Services Subgroup
Division 30–39
Site and Infrastructure Subgroup
Division 40–49
Process Equipment Subgroup

FIGURE 1.5 Structure of the MasterFormat, showing its separation into two groups—(i) Procurement and Contracting Requirements group and (ii) Specifications group. The Specifications group is further divided into five subgroups. Each subgroup is divided into a number of divisions.



50 Divisions of the MasterFormat

PROCUREMENT AND CONTRACTING REQUIREMENTS GROUP

Division 00 Procurement and Contracting Requirements

SPECIFICATIONS GROUP

Div. 01 General Requirements

FACILITIES CONSTRUCTION SUBGROUP

Div. 02 Existing Conditions
Div. 03 Concrete
Div. 04 Masonry
Div. 05 Metals
Div. 06 Wood, Plastics, and Composites
Div. 07 Thermal and Moisture Protection
Div. 08 Openings
Div. 09 Finishes
Div. 10 Specialities
Div. 11 Equipment
Div. 12 Furnishings
Div. 13 Special Construction
Div. 14 Conveying Equipment
Div. 15 Reserved for Future Expansion
Div. 16 Reserved for Future Expansion
Div. 17 Reserved for Future Expansion
Div. 18 Reserved for Future Expansion
Div. 19 Reserved for Future Expansion

FACILITIES SERVICES SUBGROUP

Div. 20 Reserved for Future Expansion
Div. 21 Fire Suppression
Div. 22 Plumbing
Div. 23 Heating, Ventilating, and Air Conditioning
Div. 24 Reserved for Future Expansion
Div. 25 Integrated Automation
Div. 26 Electrical
Div. 27 Communications
Div. 28 Electronic Safety and Security
Div. 29 Reserved for Future Expansion

SITE AND INFRASTRUCTURE SUBGROUP

Div. 30 Reserved for Future Expansion
Div. 31 Earthwork
Div. 32 Exterior Improvements
Div. 33 Utilities
Div. 34 Transportation
Div. 35 Waterway and Marine Construction
Div. 36 Reserved for Future Expansion

04 00 00 MASONRY

04 01 00 Maintenance of Masonry
04 03 00 Conservation Treatment for Period Masonry
04 05 00 Common Work Results for Masonry
04 06 00 Schedules for Masonry
04 08 00 Commissioning of Masonry
04 20 00 Unit Masonry
04 21 00 Clay Unit Masonry
04 22 00 Concrete Unit Masonry
04 23 00 Glass Unit Masonry
04 24 00 Adobe Unit Masonry
04 25 00 Unit Masonry Panels
04 26 00 Single-Wythe Unit Masonry
04 27 00 Multiple-Wythe Unit Masonry
04 28 00 Concrete Form Masonry Units
04 29 00 Engineered Unit Masonry
04 40 00 Stone Assemblies
04 41 00 Dry-Placed Stone
04 42 00 Exterior Stone Cladding
04 43 00 Stone Masonry
04 50 00 Refractory Masonry

Div. 37 Reserved for Future Expansion
Div. 38 Reserved for Future Expansion
Div. 39 Reserved for Future Expansion

PROCESS EQUIPMENT SUBGROUP

Div. 40 Process Interconnections
Div. 41 Material Processing and Handling Equipment
Div. 42 Process Heating, Cooling, and Drying Equipment
Div. 43 Process Gas and Liquid Handling, Purification, and Storage Equipment
Div. 44 Pollution and Waste Control Equipment
Div. 45 Industry-Specific Manufacturing Equipment
Div. 46 Water and Wastewater Equipment
Div. 47 Reserved for Future Expansion
Div. 48 Electrical Power Generation
Div. 49 Reserved for Future Expansion

FIGURE 1.6 MasterFormat divisions. The first few sections (Level 2 details) of Masonry division have been highlighted in a box. Level 3 details would show further divisions of a section. For example, 04 23 13 covers the specifications of vertical glass unit masonry, 04 23 16 covers glass unit masonry floors, and 04 23 19 covers glass unit masonry skylights.

RECOLLECTING MASTERFORMAT DIVISION SEQUENCE

Architectural design typically involves Divisions 02 to 14 of the Facilities Construction subgroup. Although the basis for sequencing the Divisions in this subgroup is far more complicated, the first few divisions (that are used in virtually all buildings) may be deduced by visualizing the sequence of operations required in constructing the simple building shown in Figure 1.7. The building consists of load-bearing masonry walls, steel roof joists, and wood roof deck.

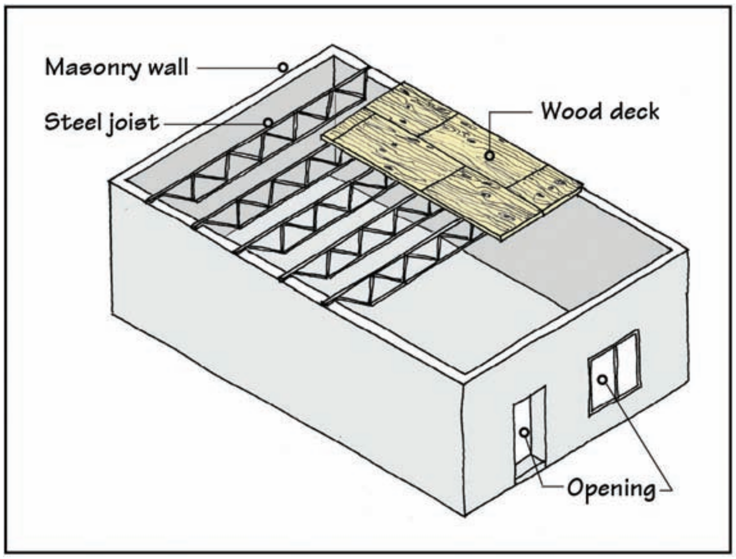


FIGURE 1.7 A simple load-bearing masonry wall building with steel roof joists and wood roof deck, used as an aid to recalling the sequence of first few divisions of the MasterFormat.

NOTE

Difference Between Specialties (Division 10) and Special Construction (Division 13)

Specialties (Division 10) includes prefabricated items such as marker boards, chalkboards, tackboards, lockers, shelves, grilles and screens, louvers and vents, flagpoles, manufactured fireplaces, and demountable partitions.

Special Construction (Division 13) includes items that are generally site fabricated but are not covered in other divisions, such as air-supported fabric structures, swimming pools, ice rinks, aquariums, planetariums, geodesic structures, and sound and vibration control.

Obviously, the first operation in constructing such a building is to excavate for foundations and lay below-ground utility lines (water supply, sewage, electrical and telecommunication lines, etc.). Because excavation deals with earthwork, MasterFormat includes it in Division 31 (Site and Infrastructure subgroup). After earthwork, the next operation is to construct foundations. Because foundations are typically made of concrete, *Concrete* is Division 03. After the foundations have been completed, masonry work for the walls can begin. Thus, *Masonry* is Division 04. After the walls are completed, steel roof joists can be placed. Thus, Division 05 is *Metals*. The installation of wood roof deck follows that of the steel joists. Hence, *Wood, Plastics,* and *Composites* constitute Division 06.

After the roof deck is erected, it must be insulated and protected against weather. Therefore, *Thermal and Moisture Protection* is Division 07. Roofing and waterproofing (of basements) are part of this division, as are insulating materials and joint sealants. The next step is to protect the rest of the envelope; hence, Division 08 is *Openings*. All doors and windows are part of this division, regardless of whether they are made of steel, aluminum, or wood.

With the envelope protected, finish operations, such as those involving the interior drywall, flooring, and ceiling, can begin. Thus, Division 09 is *Finishes*. Division 10 is *Specialties*, which consists of several items that cannot be included in the previous divisions, such as toilet partitions, lockers, storage shelving, and movable partitions.

Obviously, the building must now receive all the necessary office, kitchen, laboratory, or other equipment. Thus, Division 11 is *Equipment*. Division 12 is *Furnishings*, followed by *Special Construction* (Division 13) and *Conveying Equipment* (Division 14).

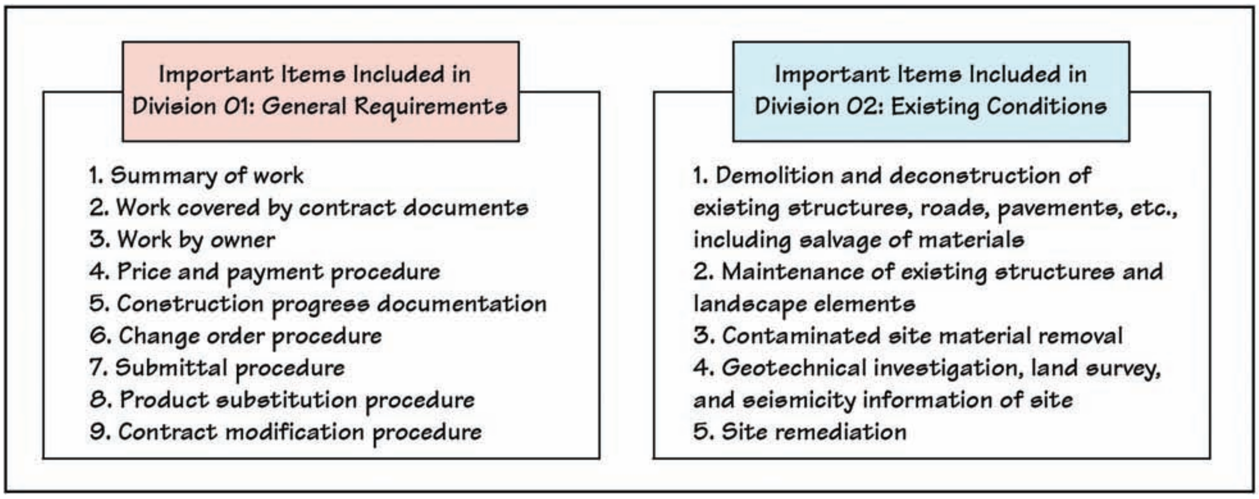
DIVISION 01 AND DIVISION 02

Before beginning with the coverage of individual materials and products, the MasterFormat covers items that apply to all of them, such as price and payment procedure, product substitution procedure, and contract modification procedure. These items are included in Division 01, titled as *General Requirements*, and illustrated in Figure 1.8. This illustration also provides items covered in Division 02—*Existing Conditions*.

Division 01 comes into effect during the construction phase, but all parties involved in the project (particularly the owner and the contractor) must know of their respective roles and obligations, detailed in this division, before signing the construction contract. By contrast Division 00, discussed in Section 1.7, comes into effect when the project is ready for soliciting bids for construction, that is, during the preconstruction phase.

MASTERFORMAT AND CONSTRUCTION-RELATED INFORMATION

Familiarity with MasterFormat is required to prepare the project manual and write the specifications for the project. It is also helpful in filing and storing construction information in an office. Material manufacturers also use MasterFormat division numbers in catalogs and publications provided to design and construction professionals. MasterFormat is also helpful when seeking information about a construction material or system, as any serious student of construction (architect, engineer, or builder) must frequently do.



Important Items Included in Division 01: General Requirements

1. Summary of work
2. Work covered by contract documents
3. Work by owner
4. Price and payment procedure
5. Construction progress documentation
6. Change order procedure
7. Submittal procedure
8. Product substitution procedure
9. Contract modification procedure

Important Items Included in Division 02: Existing Conditions

1. Demolition and deconstruction of existing structures, roads, pavements, etc., including salvage of materials
2. Maintenance of existing structures and landscape elements
3. Contaminated site material removal
4. Geotechnical investigation, land survey, and seismicity information of site
5. Site remediation

FIGURE 1.8 Important items included in MasterFormat Division 01 and Division 02.

1.6 THE CONSTRUCTION TEAM

The construction of even a small building involves so many specialized skills and trades that the work cannot normally be undertaken by a single construction firm. Instead, the work is generally done by a team consisting of the general contractor (GC) and a number of specialty subcontractors, Figure 1.9. Thus, a project may have roofing, window and curtain wall, plumbing, and heating, ventilation, and air-conditioning (HVAC) subcontractors among others, in addition to the general contractor. The general contractor's own work may be limited to certain components of the building (such as the structural components—load-bearing walls, reinforced concrete beams and columns, and roof and floor slabs), with all the remaining work subcontracted.

In contemporary projects, however, the trend is toward the general contractors not performing any actual construction work but subcontracting the work entirely to various subcontractors. Because the subcontractors are contracted by the general contractor, only the GC is responsible and liable to the owner.

In some cases, a subcontractor will, in turn, subcontract a portion of his or her work to another subcontractor, referred to as a *second-tier subcontractor*. In that case, the GC deals only with the subcontractor, not the second-tier subcontractor.

Whether the GC performs part of the construction work or subcontracts the entire work, the key function of the GC is the overall management of construction. This includes coordinating the work of all subcontractors, ensuring that the work done by them is completed in accordance with the contract documents, and ensuring the safety of all workers on the site. A GC with a good record of site safety not only demonstrates respect for the workers but also improves the profit margin by lowering the cost of construction insurance.

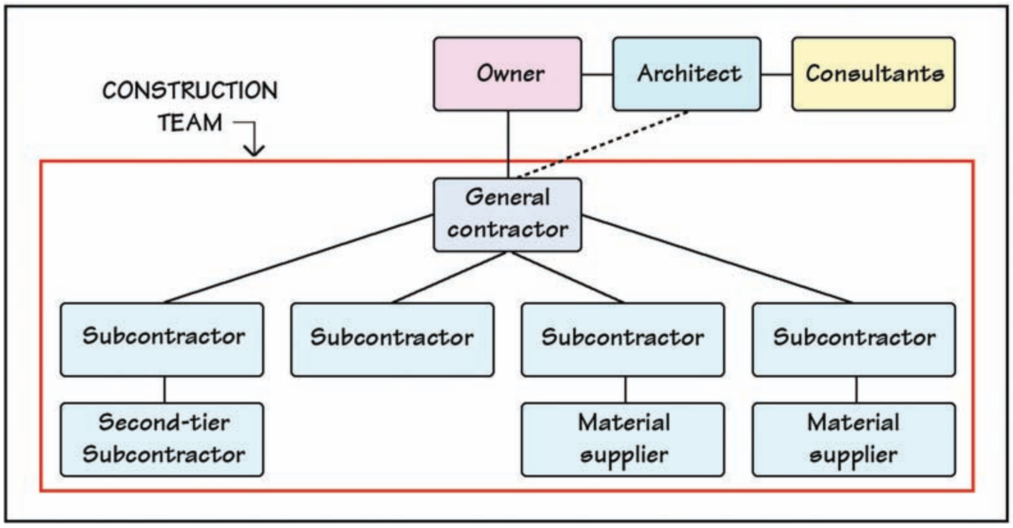


FIGURE 1.9 The construction team and their interrelationships with each other and the owner. A solid line in this illustration indicates a contractual relationship between parties. A dashed line indicates a communication link. The relationships shown here are not absolute and may change somewhat with the nature of the project.

DESIGN AND CONSTRUCTION CONTRACTS AS TWO-PARTY CONTRACTS

It is important to note at this stage that all design and construction contracts are two-party contracts, such as owner-architect contract, owner-GC contract, architect-consultant contracts, and GC-subcontractor contracts. Multiparty design or construction contracts do not exist (except in the integrated project delivery method, described in Section 1.17).

1.7 PRECONSTRUCTION PHASE: THE BIDDING DOCUMENTS

The preconstruction phase comprises two important activities: preparation of bidding documents (also called *bid package*) and the selection of the GC. The bidding documents are prepared by the architect with the help of the entire design team. They are documents that are used by the GC to bid for the construction of the project. They include (i) construction documents, which comprises construction drawings and specifications (Divisions 01 to 49) and (ii) Division 00.

Division 00, titled as *Procurement and Contracting Requirements*, contains legal and contractual information that the GC must be aware of before preparing the bids. For the ease of grasping its contents, Division 00 may be divided into four parts: (a) bid procurement requirements, (b) contract requirements, (c) contract administration, and (d) available project information, Figure 1.10.

As shown in Figure 1.10, the *bid procurement* part of Division 00 refers to items that a GC will typically not deal with after signing the contract, such as instruction to bidders, prebid meetings, and bid bond information. The *contract requirements* part contains owner-GC agreement, conditions of contract, etc. *Contract administration* includes performance and payment bond details, and requirements for certificates of substantial and final completion. *Available project information* relates to land survey, geotechnical information, geophysical information, etc. An important component of geophysical information is the degree of seismicity of the site.

The bidding documents may also contain addenda. An addendum refers to a document that is added to the original construction documents during the bidding period because of the errors or omissions observed after the bidding documents have been released to the bidders. An addendum may also become necessary in response to questions raised during a prebid meeting by the prospective bidders.

After the contract has been awarded to the successful bidder, the bidding documents (with owner's and GC's signatures on documents where needed, and blank forms in Division 00 completed) become the contract documents. The contract documents may also include modifications to owner-GC contract after the execution of the original contract. These modifications must be mutually agreed to between the owner and the GC per contract modification procedure described in Division 01. The items included in contract documents are shown in Figure 1.11, which also illustrates the differences between construction documents, bidding documents, and contract documents.

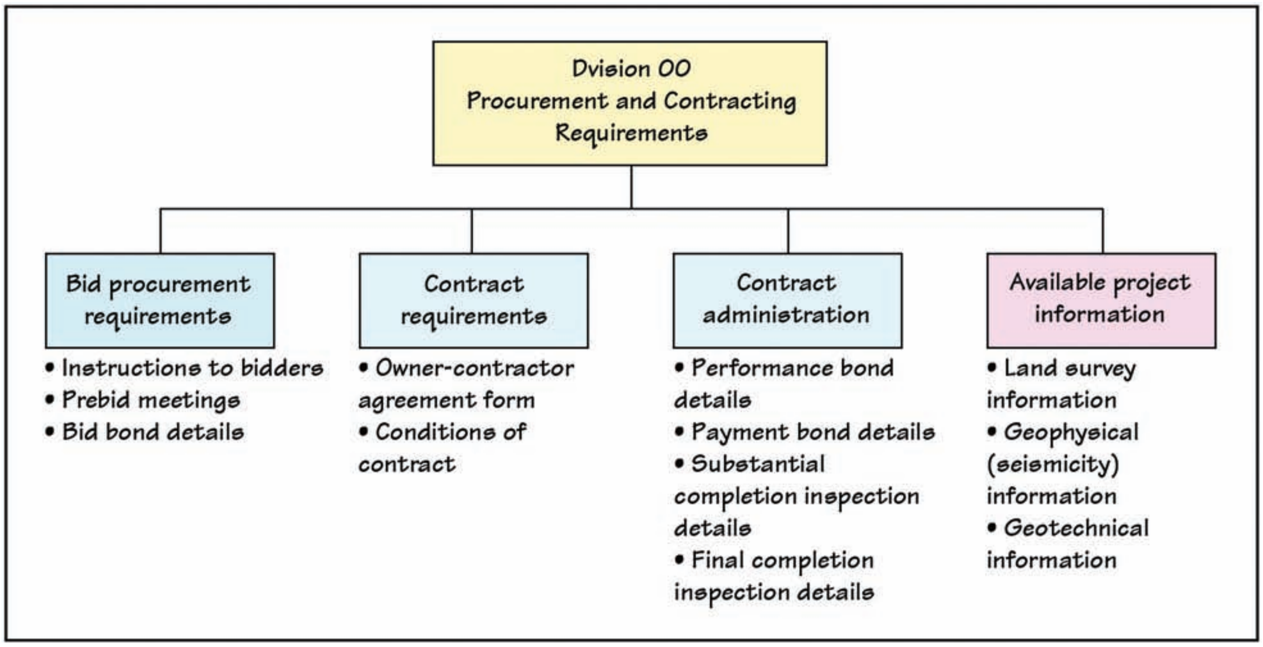

Dvision 00
Procurement and Contracting
Requirements
Bid procurement requirements
Contract requirements
Contract administration
Available project information
• Instructions to bidders
• Prebid meetings
• Bid bond details
• Owner-contractor agreement form
• Conditions of contract
• Performance bond details
• Payment bond details
• Substantial completion inspection details
• Final completion inspection details
• Land survey information
• Geophysical (seismicity) information
• Geotechnical information

FIGURE 1.10 Important contents of MasterFormat Division 00.

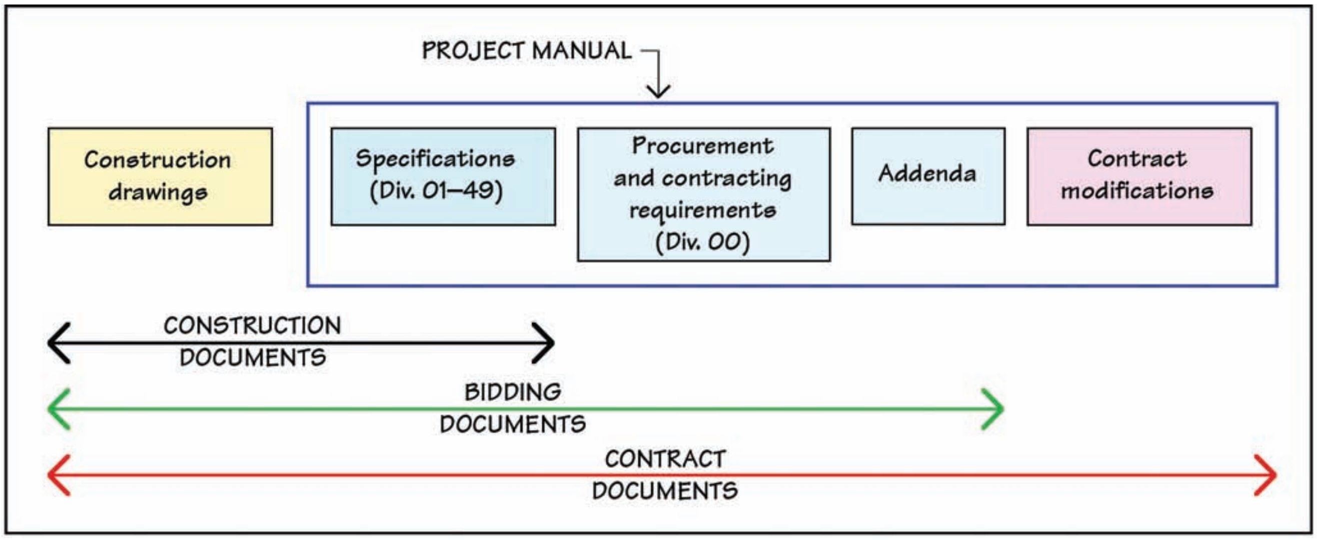

PROJECT MANUAL
Construction drawings
Specifications (Div. 01–49)
Procurement and contracting requirements (Div. 00)
Addenda
Contract modifications
CONSTRUCTION DOCUMENTS
BIDDING DOCUMENTS
CONTRACT DOCUMENTS

FIGURE 1.11 Differences among construction documents, bidding documents (also called "bid package"), and contract documents.

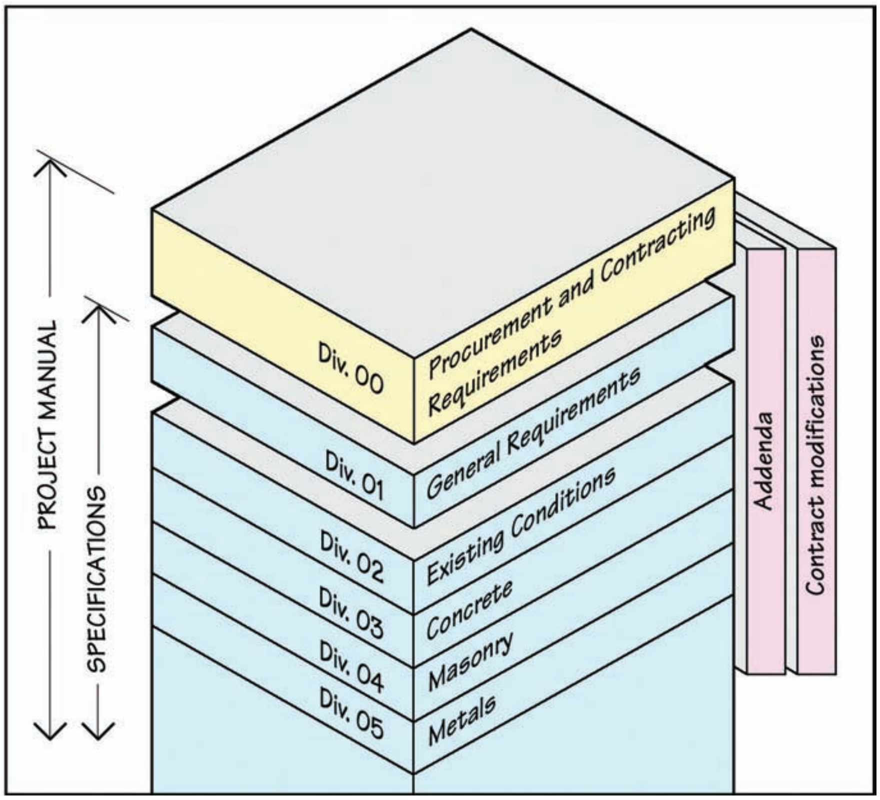

PROJECT MANUAL
SPECIFICATIONS
Div. 00
Procurement and Contracting Requirements
Div. 01
General Requirements
Div. 02
Existing Conditions
Div. 03
Concrete
Div. 04
Masonry
Div. 05
Metals
Addenda
Contract modifications

FIGURE 1.12 Contents of a typical project manual.

Although no owner would like to modify the contract, contract modifications are not uncommon. The reason, as stated in the introduction to this chapter, is that the construction of a typical building, unlike a manufactured product, is one-off entity, which may be subjected to unforeseen situations. Causes such as significant change in project scope (additive or deductive), design error or omission, nonavailability of materials due to national emegency, and extreme weather conditions may require contract modification.

PROJECT MANUAL

Project specifications (Division 01 to 49), Division 00, addenda, and contract modifications are bound together into a document called the *project manual*, Figure 1.12. In other words, the project manual comprises the contract documents minus the construction drawings.

1.8 PRECONSTRUCTION PHASE: THE SURETY BONDS

It is essential that the GCs bidding for the project are qualified by virtue of their financial resources and a successful record of contracting experience to undertake the project of the size and complexity of the owner's project. Therefore, a reliable and just process of screening the GCs must be used, which is achieved by requiring the GCs to provide bonds to the owner.

A bond is a form of surety, which ensures that if the GC fails to fulfill contractual obligations, there will be a financially sound third party—referred to as the *surety* (also called the *guarantor* or *bonding company*)—available to take over those unfulfilled obligations of the GC. The bond is, therefore, a form of insurance that the GC buys from a surety—a bonding company.

There are three types of surety bonds in most building projects. A few others may be required in some special projects. The three types of bonds are: (i) bid bond, (ii) performance bond, and (iii) payment bond, each with a unique purpose, as described hereunder, and illustrated in Figure 1.13.

BID BOND

The purpose of the bid bond (also called the *bid security bond*) is to exclude frivolous bidders. It ensures that, if selected by the owner, the bidder (GC) will be able to enter into a contract with the owner based on the bidding requirements, and that the bidder will be able to obtain performance and payment bonds from an acceptable bonding company.

A bid bond is required at the time the GC submits the bid for the project. If the GC refuses to enter into an agreement or is unable to provide the required performance and payment bonds, the bonding company is obliged to pay a penalty (bid security amount) to the owner—usually between 5% and 10% of the project's anticipated cost.

PERFORMANCE BOND

The performance bond is required by the owner before entering into an agreement with the successful GC. The performance bond ensures that if, after the award of the contract, the GC is unable to perform the work as required by the contract documents, the bonding company will provide sufficient funds for the completion of the project.

A performance bond protects the owner against default by the GC or by those for whose work the GC is responsible, such as the subcontractors. For that reason, the GC will generally require a performance bond from all major subcontractors.

PAYMENT BOND

A payment bond (also referred to as a *labor and materials bond*) ensures that those providing labor, services, and materials for the project—such as the subcontractors and material suppliers—will be paid by the GC. In the absence of the payment bond, the owner may be held liable to those subcontractors and material suppliers whose services and materials have been invested in the project. This liability exists even if the owner has paid the GC for the work of these subcontractors and material suppliers.

PROS AND CONS OF BONDS

The bonds are generally mandated for a publicly funded project. In a private project, the owner may waive the bonds, particularly the bid bond. This saves the owner some money because although the cost of a bond (the premium) is paid by the GC, it is in reality paid by the owner since the GC adds the cost of the bond to the bid amount.

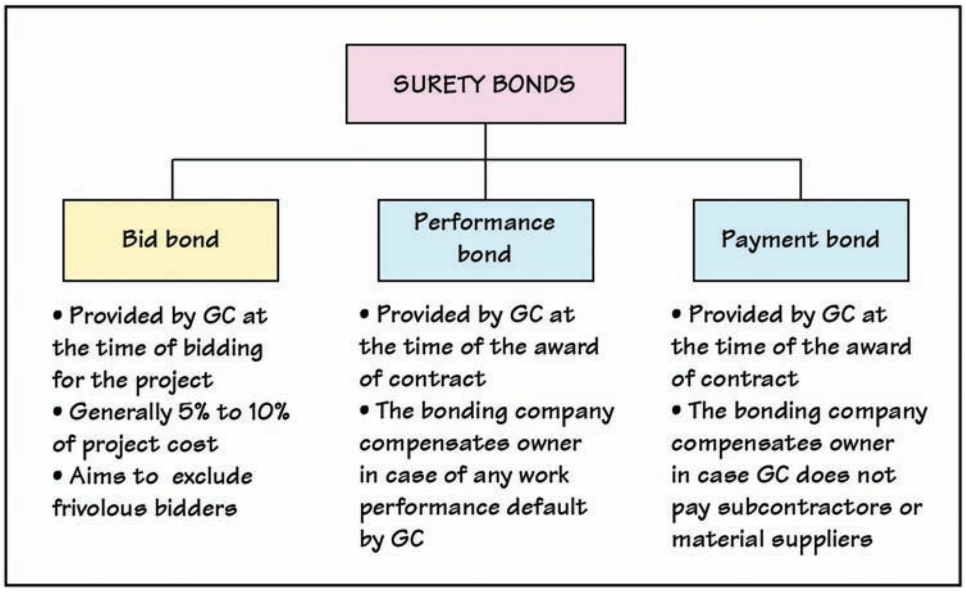

SURETY BONDS
Bid bond
Performance bond
Payment bond
• Provided by GC at the time of bidding for the project
• Generally 5% to 10% of project cost
• Aims to exclude frivolous bidders
• Provided by GC at the time of the award of contract
• The bonding company compensates owner in case of any work performance default by GC
• Provided by GC at the time of the award of contract
• The bonding company compensates owner in case GC does not pay subcontractors or material suppliers

FIGURE 1.13 Details of three surety bonds used in construction projects.

Despite their cost, most owners consider the bonds (particularly the performance and payment bonds) a good value because they eliminate the financial risks of construction. The bid bond is unnecessary in an invitational bidding method where the owner knows the GC's financial standing and the ability to perform. However, where uncertainty exists, a bid bond provides an excellent prequalification screening of the GC. Responsible GCs and subcontractors generally maintain a close and continuous relationship with their bonding companies. Therefore, the bonding company's knowledge of a contractor's financial and contracting capabilities far exceeds that of most owners or architects (as the owner's representative).

1.9 PRECONSTRUCTION PHASE: SELECTING THE GENERAL CONTRACTOR AND PROJECT DELIVERY

After the bidding documents are ready, the selection of the GC is next obvious and a significant step forward. A number of selection methods exist. They differ from each other depending on:

a. the basis of selection—open competition, limited competition, or negotiation with selected GCs,
b. the timing of selection—stage of the project at which the selection is made—predesign phase, design phase, or preconstruction phase,
c. the GC's role during the design phase, and
d. the level of coordination between the design and construction teams through all phases of the project.

These methods are called the *project delivery methods*. Some of the most commonly used project delivery methods are:

- Design-bid-build (DBB) method
- Design-negotiate-build (DNB) method
- Construction manager at risk (CMAR) method
- Design-build (DB) method
- Integrated project delivery (IPD) method

The DBB is the oldest and most familiar method of project delivery. It has stood the test of time and enjoys the largest market share. The IPD is the latest method and still evolving in details with limited amount of industry consensus. Figure 1.14 gives the current approximate market shares of various methods [Refs. 1.2, 1.3], and the table "Project Delivery Methods at a Glance", at the end of this chapter, provides a synopsis of their pros and cons. The reader is urged to go through this table to obtain a bird's-eye view of various methods.

Regardless of the method selected, the essential features of construction and postconstruction phases are almost identical in all methods. Therefore, the activities involved in these two phases are covered first. In this coverage, we will assume that the GC has been selected and the construction has commenced. After the discussion of construction and postconstruction phases, the project delivery methods are covered in Sections 1.13 through 1.17.

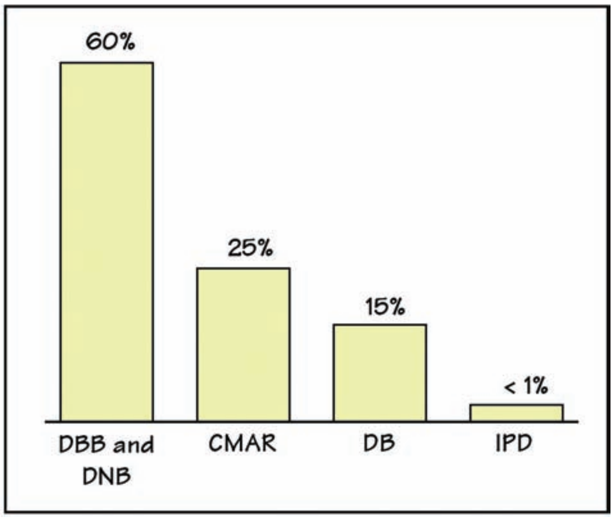


FIGURE 1.14 The current approximate market shares of various project delivery methods [Refs. 1.2, 1.3].

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

12. MasterFormat has been developed by the
- **a.** Construction Specifications Institute.
- **b.** American Society for Testing and Materials.
- **c.** American National Standards Institute.
- **d.** American Institute of Architects.
- **e.** Associated General Contractors of America.

13. MasterFormat consists of
- **a.** 20 divisions.
- **b.** 30 divisions.
- **c.** 40 divisions.
- **d.** 50 divisions.
- **e.** none of the above.

14. In MasterFormat, Division 02 refers to
- **a.** Procurement and Contracting Requirements.
- **b.** General Requirements.
- **c.** Masonry.
- **d.** Metals.
- **e.** none of the above.

15. In MasterFormat, Division 04 refers to
- **a.** General Requirements.
- **b.** Existing Conditions.
- **c.** Masonry.
- **d.** Metals.
- **e.** none of the above.

16. In MasterFormat, windows are part of
- **a.** Division 04.
- **b.** Division 05.
- **c.** Division 06.
- **d.** Division 07.
- **e.** none of the above.

17. In MasterFormat, roofing is part of
- **a.** Division 07.
- **b.** Division 08.
- **c.** Division 09.
- **d.** Division 10.
- **e.** Division 11.

18. In MasterFormat, flooring is part of
- **a.** Division 05.
- **b.** Division 06.
- **c.** Division 07.
- **d.** Division 08.
- **e.** Division 09.

19. Who is responsible for ensuring the safety of workers on the construction site of a typical building project?
- **a.** The architect
- **b.** The structural engineer
- **c.** The general contractor
- **d.** Occupation Safety and Health Administration of the U.S. Government
- **e.** All of the above collectively

20. The bidding documents include
- **a.** construction drawings.
- **b.** construction drawings and specifications.
- **c.** construction drawings, specifications, and addenda.
- **d.** construction drawings, specifications, addenda, and contract modifications.
- **e.** none of the above.

21. A contract document set consists of
- **a.** construction drawings.
- **b.** construction drawings and specifications.
- **c.** construction drawings, specifications, and addenda.
- **d.** construction drawings, specifications, addenda, and contract modifications.
- **e.** none of the above.

22. The project manual includes the project's construction drawings.
- **a.** True
- **b.** False

23. The surety bonds used in a typical construction contract are
- **a.** bid bond, contract award bond, and completion bond.
- **b.** prescreening bond, award bond, and completion bond.
- **c.** bid bond, performance bond, and completion bond.
- **d.** bid bond, performance bond, and payment bond.
- **e.** none of the above.

24. All required surety bonds must be provided by the GCs, who are bidding for the project, along with their bids, that is, at the time of bidding.
- **a.** True
- **b.** False

25. The owner is required to provide payment bond to GC whose bid has been accepted
- **a.** at the time of executing the owner-GC agreement.
- **b.** when the owner gives the notice to GC to proceed with the work.
- **c.** within one week of the GC commencing construction.
- **d.** when the GC provides performance bond to the owner.
- **e.** none of the above.

26. A GC would usually require performance bond from
- **a.** the owner.
- **b.** the architect.
- **c.** the owner and the architect.
- **d.** the owner, architect, and the consultants.
- **e.** each major subcontractor.

27. Where the owner is sufficiently familiar and confident of the financial and contractual capabilities of the GCs bidding for the project, the owner may not require the bid bond. This reduces the total cost of construction.
- **a.** True
- **b.** False

28. Of the various project delivery methods described in the text, the oldest method is
- **a.** integrated project delivery (IPD) method.
- **b.** construction manger at risk (CMAR) method.
- **c.** design-build method (DB) method.
- **d.** design-negotiate-build (DNB) method.
- **e.** design-bid-build (DBB) method.

1.10 CONSTRUCTION PHASE: SUBMITTALS AND CONSTRUCTION PROGRESS DOCUMENTATION

The construction phase begins after the GC has been selected, contract awarded, and "notice to proceed" has been issued. The selection of a GC is a function of the chosen project delivery method. Regardless of the chosen project delivery method, the role of GC in the construction phase remains essentially the same in all of them, and the GC must conform to the work described in the contract documents.

In preparing the contract documents, the design team's aim is to communicate the design intent effectively in order to minimize missing pieces of information. However, in almost every project, there are a few items that cannot be described to absolute finality in contract documents. For these items, the design team makes its final decision based on the information sought from the GC. The entities from which the required information is obtained are called *submittals*. Typical submittals include material and product samples, product performance data, shop drawings, and mockups.

SHOP DRAWINGS

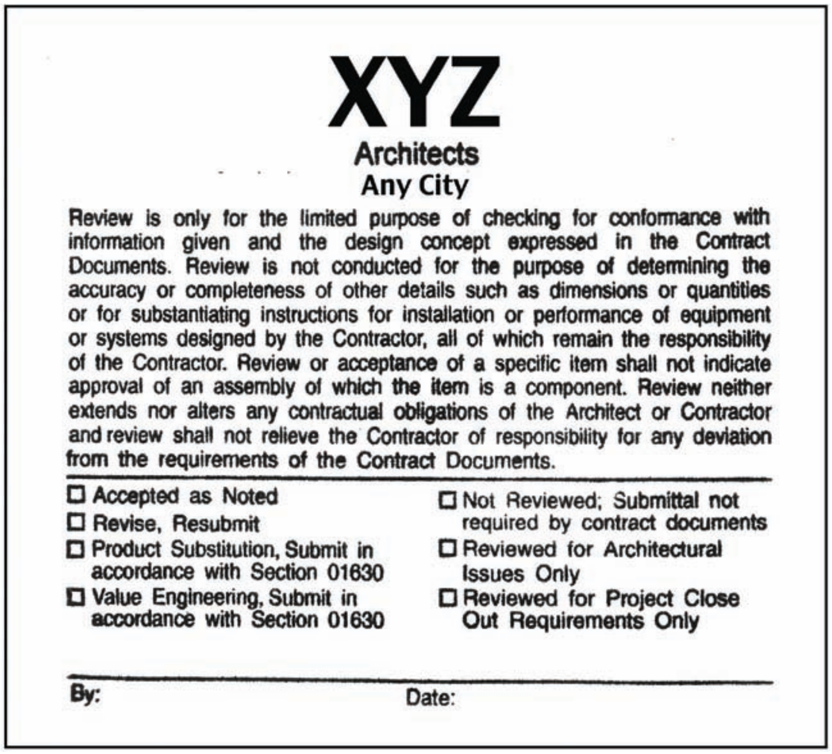
Shop drawings are required for components and products that must typically be made off-site (in a fabrication "workshop"). The need for shop drawings for certain items arises because the construction drawings do not describe them to a level of detail that makes their fabrication possible. Therefore, the fabricators generate their own drawings, referred to as *shop drawings*, to provide the higher level of detail necessary to fabricate and assemble the components.

Shop drawings are not generic, consisting of manufacturers' or suppliers' catalogs, but are exclusively prepared for the project by the manufacturer, fabricator, erector, or subcontractors. Shop drawings are a big item for structural members, such as steel columns, steel beams, and reinforcement details in reinforced concrete members. They are also required for nonstructural components. For example, an aluminum window manufacturer must produce shop drawings to show that the required windows conform with the construction drawings and the specifications. Similarly, precast concrete panels, stone cladding, and marble or granite floor coverings require shop drawings before they are fabricated and installed.

Before commencing fabrication, the subcontractors and suppliers submit the shop drawings to the GC. The GC reviews them, marks them "approved", if appropriate, and then submits them to the architect for review and approval. Subcontractors or suppliers cannot submit shop drawings directly to the architect.

The review of all shop drawings is coordinated through the architect, even though they may actually be reviewed in detail by the appropriate consultant. Thus, the shop drawings pertaining to structural components are sent to the architect and then to the structural consultant for review and approval. The subcontractor or supplier generally begins fabrication only after receiving the architect's review of the shop drawings.

The review of shop drawings by the architect is limited to checking that the work indicated therein conforms with the overall design intent shown in the contract documents, Figure 1.15. Approval of shop drawings that are later discovered to deviate from the contract documents



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Review is only for the limited purpose of checking for conformance with information given and the design concept expressed in the Contract Documents. Review is not conducted for the purpose of determining the accuracy or completeness of other details such as dimensions or quantities or for substantiating instructions for installation or performance of equipment or systems designed by the Contractor, all of which remain the responsibility of the Contractor. Review or acceptance of a specific item shall not indicate approval of an assembly of which the item is a component. Review neither extends nor alters any contractual obligations of the Architect or Contractor and review shall not relieve the Contractor of responsibility for any deviation from the requirements of the Contract Documents.

☐ Accepted as Noted
☐ Revise, Resubmit
☐ Product Substitution, Submit in accordance with Section 01630
☐ Value Engineering, Submit in accordance with Section 01630
☐ Not Reviewed; Submittal not required by contract documents
☐ Reviewed for Architectural Issues Only
☐ Reviewed for Project Close Out Requirements Only

By: Date:

FIGURE 1.15 A typical stamp used by architects to indicate the result of review of shop drawings and other submittals.

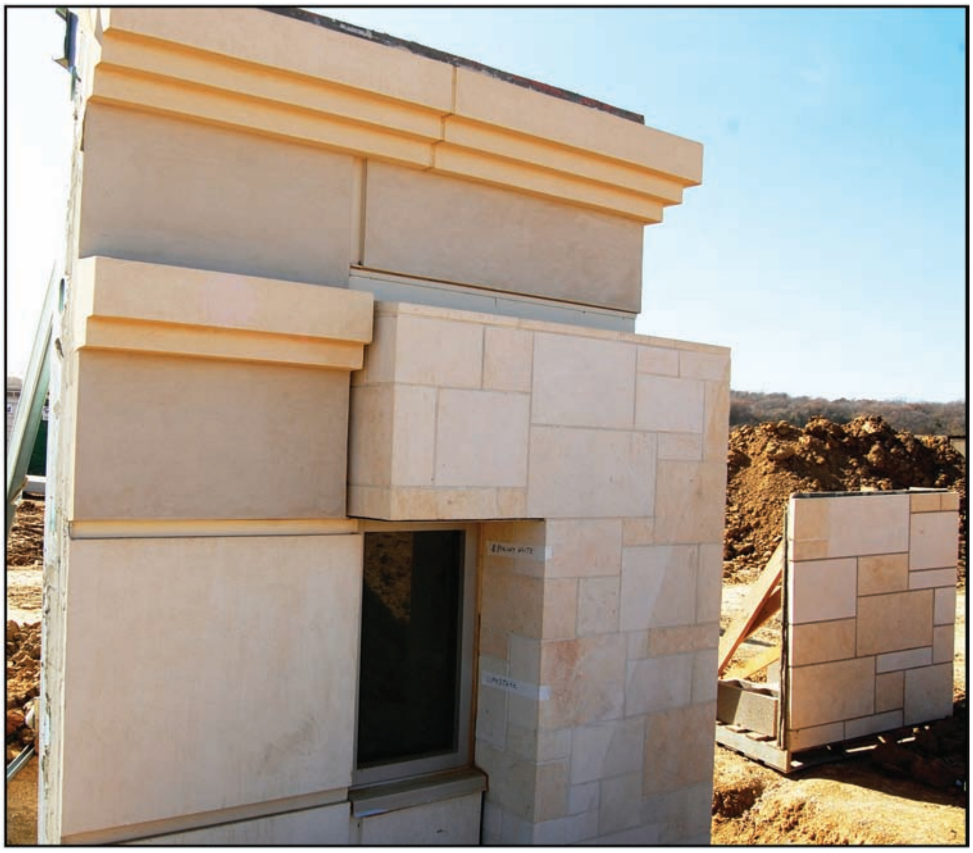


FIGURE 1.16 A typical mockup showing various finishes on the exterior facade of a building under construction. The workmanship in the finished building will be evaluated to match that of the approved mockup.

does not absolve the GC of the responsibility to comply with the contract documents for quality of materials, workmanship, or the dimensions of the fabricated components.

MOCKUPS

In addition to shop drawings, full-size mockups of one or more critical elements of the building may be required in some projects. This is done to establish the quality of materials and workmanship by which the completed work will be judged. For example, it is quite common for the architect to ask for the construction of a mockup that shows various exterior façade materials before undertaking the construction of the actual façade. Figure 1.16 shows a typical mockup of a building under construction. In some cases, the architect may require mockups of the same façade utilizing different materials, different colors, or different features to make the final design decision (see Figure 29.20).

CONSTRUCTION PROGRESS DOCUMENTATION

Keeping a complete and continuous documentation of construction is an essential part of a GC's work. Important documentation includes project correspondence, minutes of meetings, verbal conversations, weather conditions, change order logs, critical materials brought to the site, and site visits by third party (design team members, building inspection personnel from the city, OSHA staff, etc.). (OSHA is an acronym for Occupational Safety and Health Administration of the U.S. Government.)

In many contemporary projects, the owner requires the GC to install web-based cameras (webcam) on the site for a continuous, photographic documentation of construction progress, Figure 1.17. This digital imagery provides real-time (24 × 7) and remote access of construction progress to the owner and the design team, in addition to time-lapse videos if needed. Modern webcam technology provides high-resolution images that help detect breach of site safety conditions, theft of materials, and such other activities. Images of construction obtained through drones and helicopters are also common, but they do not provide continuous documentation.

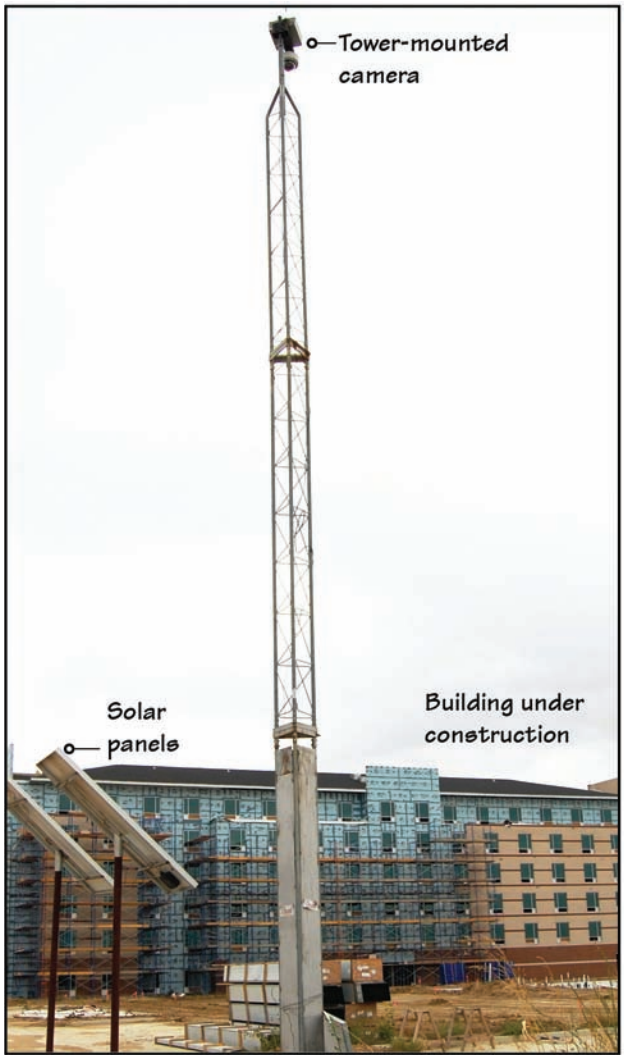


FIGURE 1.17 A tower-mounted camera takes regular photographs of the construction of the building shown. The solar panels power an array of batteries that, in turn, power the camera. The batteries are housed in a box below the panels, not visible in the photograph.

1.11 CONSTRUCTION PHASE: CONTRACT ADMINISTRATION

The GC will normally have an inspection process to ensure that the work of all subcontractors is progressing as indicated in the contract documents and that the work meets the standards of quality and workmanship. On smaller projects, this may be done by the project superintendent. On large projects, a team of quality-assurance inspectors generally assists the contractor's project superintendent. These inspectors are individuals who, by training and experience, are specialized in their own areas of construction—for example, concrete, steel, or masonry.

Additional quality control is required by the contract through the use of independent testing laboratories. For instance, structural concrete brought to the site must be verified for strength and other properties by independent concrete-testing laboratories.

Leaving quality control of materials and performance entirely in the hands of the GC is considered inappropriate. It can render the owner vulnerable to omissions and errors in the work, and it places an additional legal burden on the GC. Therefore, the owner usually retains the services of the project architect to provide a third-party level of scrutiny to administer the construction contract. If not, the owner will retain another independent architect, engineer, or inspector to provide construction contract administration services.

ARCHITECT'S OBSERVATION OF CONSTRUCTION

The architect's role during the construction phase has evolved over the years. There was a time when architects provided regular supervision of their projects during construction, but the liability exposure resulting from the supervisory role became so adverse for the architects that they have been forced to relinquish this responsibility. Instead, the operative term for the architect's role during construction is referred to as *field observation* of the work.

The observational role still allows the architects to verify that their drawings and specifications are transformed into reality just as they had conceived. It also provides a sufficient safeguard against the errors caused by the contractors' misinterpretation of contract documents in the absence of the architects' clarification and interpretation.

The shift in the architect's role to observer of construction also recognizes the important and entirely independent role that the GC must play during construction. This recognition provides full authority to the GC to proceed with the work in the manner that the GC deems appropriate. This reinforces the earlier statements that:

- The architect determines the *what* and *where*.
- The GC determines the *how* (means and methods) and *when* (sequence) of construction.

In other words, daily supervision or superintendence of construction is the function of the GC—the most competent person to fulfill this role. The architect provides periodic observation and evaluation of the GC's work and notifies the owner if the work is not in compliance with the intent of the contract documents. This underscores the division between the responsibilities of the architect and the GC during construction.

Note that by providing observation, the architect does not certify the GC's work. Nor does the observation relieve the GC of his or her responsibilities under the contract. The GC remains fully liable for any error that has not been discovered through the architect's observation. However, the architect may be held liable for all or part of the work observed, should the architect fail to detect or provide timely notification of work not conforming with the contract documents. This omission is known as *failure to detect*.

Because many components can be covered up by other items over days or hours, the architect should visit the construction site at regular intervals, as appropriate to the progress of construction. For example, earthwork covers foundations and underground plumbing, and gypsum board covers ceiling and wall framing. Observing the work after the components are hidden defeats the purpose of observation.

On some projects, a resident project architect or engineer may be engaged by the architect, at an additional cost to the owner, to observe the work of the GC. Under the conditions of the contract, the GC is generally required to provide this person with an on-site office, water, electricity, a telephone, and other necessary facilities.

INSPECTION OF WORK

There are only two times during the construction of a project that the architect makes an exception to being an observer of construction. At these times, the architect inspects the work. These inspections are meant to verify the GC's claim that the work is: (a) substantially complete and (b) fully complete, and hence is ready for the final payment. These inspections, explained in Section 1.12, are referred to as:

- Substantial completion inspection
- Final completion inspection

PAYMENT CERTIFICATIONS

In addition to construction observation and inspection, there are several other duties the architect must discharge in administering the contract between the owner and the GC. These are outlined in the box "Summary of Architect's Functions as Construction Contract Administrator". Certifying (validating) the GC's periodic requests for payment against the work done and the materials stored at the construction site is perhaps the most critical of these functions.

An application for payment (typically made once a month unless stated differently in the contract) is followed by the architect's evaluation of the work and necessary documentation to verify the GC's claim. Because the architect is not involved in day-to-day supervision, the issuance of the certificate of payment by the architect does not imply acceptance of the quality or quantity of the GC's work. However, the architect has to be judicious and impartial to both the owner and the GC, and perform within the bounds of the contract.

CHANGE ORDERS

There is hardly a construction project that does not require changes after construction has begun. The contract between the owner and the GC recognizes this fact and includes provisions for the owner's right to order a change and the GC's obligation to accept the change order in return for an equitable price adjustment. Here again, the architect performs a quasi-judicial role to arrive at a suitable agreement and price between the owner and the GC.

Note that the change orders refer to minor changes in the project and are unilaterally made by the owner. Where the project requires significant modifications, the contract must be modified and the modifications are to be mutually agreed upon between the owner and the GC. Thus, a construction contract differentiates between "changes" and "modifications".

NOTE

Summary of the Architect's Functions as Construction Contract Administrator

- Observe construction
- Inform the owner of the progress of work
- Guard the owner against defects and deficiencies
- Review and approve shop drawings, mockups, and other submittals
- Prepare change orders, if required
- Review correspondence between the owner and the contractor and take action if required
- Prepare certificates of payment
- Make the substantial completion inspection
- Make the final completion inspection
- Review manufacturers' and suppliers' warranties and other project closeout documentation and forward them to the owner
- Make a judicious interpretation of the contract between the owner and the contractor when needed

NOTE

Value Engineering

Value engineering (VE) is the science of obtaining balance among cost, reliability, and performance of a product or project. VE is commonly used in building projects when the project's cost begins to exceed its budget. It relates to the substitution for a product or assembly that is part of the original design with an alternative that provides acceptable performance, reliability, and aesthetics at a lower cost. Some change orders in a project may be driven by VE.

1.12 POSTCONSTRUCTION PHASE: PROJECT CLOSEOUT

Once the project is sufficiently complete, the GC will ask the architect to conduct a substantial completion inspection to confirm that the work is complete in most respects. By doing so, the GC implies that the work is complete enough for the owner to occupy the facility and start using it, even though there might be cosmetic and minor work yet to be completed.

The GC's request for substantial completion inspection by the architect should include a list of incomplete portions of the work (to be completed), referred to as the *punch list*. The punch list, which is prepared by the GC, is used by the architect as a checklist to review all work, not merely the incomplete portions of the work. If the architect's inspection discloses incomplete items not included in the GC's punch list, they are added to the list by the architect.

The substantial completion inspection is also conducted by the architect's consultants, either with the architect or separately. Incomplete items discovered by them are also added to the punch list. If the additional items are excessive, the architect may ask the GC to complete the selected items before rescheduling the substantial completion inspection.

CERTIFICATE OF OCCUPANCY AND GC'S REQUEST FOR SUBSTANTIAL COMPLETION INSPECTION

The GC is required to secure a certificate of occupancy before requesting substantial completion inspection by the architect and the design team. The certificate of occupancy is provided by the authority having municipal jurisdiction over the project—usually the city where the project is permitted and built. The certificate of occupancy confirms that all appropriate inspections and approvals, required by the authority having jurisdiction, have taken place, the project is safe to use and occupy, and that the site has been cleared of the GC's temporary facilities so that the owner can occupy the building without obligations to any authority.

SUBSTANTIAL COMPLETION—THE MOST IMPORTANT PROJECT DATE

In addition to the certificate of occupancy, the GC must submit all required guaranties and warranties from the manufacturers of equipment and materials and the specialty subcontractors and installers used in the building. For instance, the manufacturers of roofing materials, windows, curtain walls, mechanical equipment, etc. warrant their products for specified time periods. These warranties are in addition to the standard one-year correction period between the owner and the GC.

The warranties are to be given to the architect at the time of substantial completion for review and transmission to the owner. Because the obligatory one-year correction period between the owner and the GC, as well as other extended-time warranties, begins from the date of substantial completion of the project, the substantial completion date is an important project closeout event. That is why the GC is allowed a brief time interval to complete the work fully after the successful substantial completion inspection.

A successful substantial completion inspection results in the GC receiving the certificate of substantial completion from the architect. An important part of this certificate is the date of substantial completion, which implies that the GC is no longer liable for the maintenance (cleaning and upkeep), utility costs, insurance, and security of the project. These responsibilities and liabilities are transferred to the owner.

FINAL COMPLETION INSPECTION

After the GC carries out all the corrective work identified during the substantial completion inspection and so informs the architect, the architect (with the assistance of the consultants) carries out the final inspection of the project. If the final inspection passes, certification for final payment is issued by the architect, which entitles the GC to receive the final payment from the owner.

Before the certification for final completion is executed by the architect, and finally by the owner, the owner receives the record documents, keys and key schedule, equipment manuals, and other specified necessities. Additionally, the owner receives all legal documentation to indicate that the GC will be responsible for claims made by any subcontractor, manufacturer, or other party with respect to the project.

RECORD DOCUMENTS (AS-BUILT DOCUMENTS)

As previously stated, minor design changes are often made during the construction of a project. These changes must be recorded for the benefit of the owner should the owner wish to alter or expand the building in the future. Therefore, after the building has been completed, the GC is required to provide a set of record drawings (previously known as *as-built drawings*). These drawings reflect the changes that were made during the course of construction by the GC.

In addition to record drawings, record specifications, as well as a set of approved shop drawings, are usually required to complete the record document package delivered to the owner.

1.13 PROJECT DELIVERY METHOD: DESIGN-BID-BUILD METHOD

In the design-bid-build method, the GC is selected through competition. The owner obtains multiple bids for the project from which the GC, who provides the "best value for money", is selected. Within this overall approach, several versions are available to suit the requirements of the project and the particular needs of the owner. Collectively, these delivery versions are referred to as the *design-bid-build* (DBB) method because in this version, the design, bid, and construction phases of a project are sequential, and one phase does not begin until the previous phase has been completed, as graphically shown in Figure 1.18. Following are three commonly used versions of the DBB method of delivery.

- DBB Method—competitive sealed bidding (open bidding)
- DBB Method—competitive sealed proposal
- DBB Method—invitational bidding (closed bidding)

DBB METHOD—COMPETITIVE SEALED BIDDING

The award of a construction contract to the GC is based on open bidding process, commonly called *competitive sealed bidding*. This refers to the process by which "qualified" GCs are invited to bid on the project; the "qualification" comes from the requirement of the bid bond. The invitation can be issued through advertisements in newspapers and trade publications, but web-based construction project bidding platforms, also called *construction project procurement opportunities*, are commonly used. The GCs regularly access these Web sites to keep abreast of the opportunities.

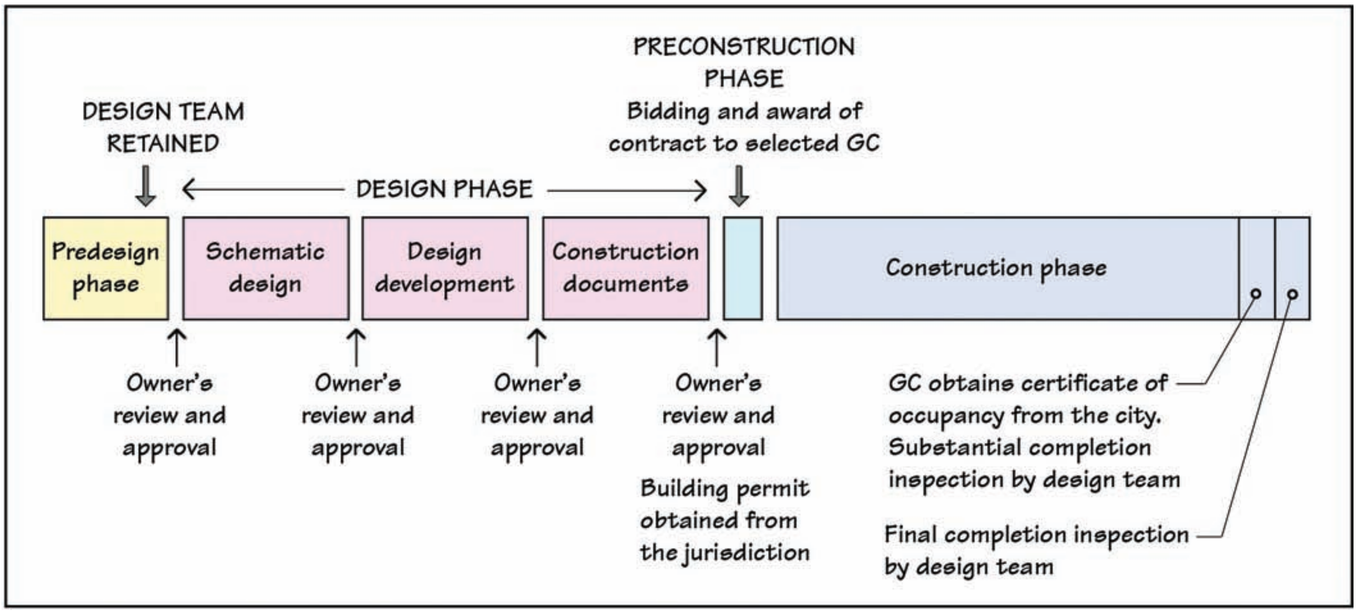

PRECONSTRUCTION PHASE
Bidding and award of contract to selected GC
DESIGN TEAM RETAINED
DESIGN PHASE
Predesign phase
Schematic design
Design development
Construction documents
Construction phase
Owner's review and approval
Owner's review and approval
Owner's review and approval
Owner's review and approval
Building permit obtained from the jurisdiction
GC obtains certificate of occupancy from the city. Substantial completion inspection by design team
Final completion inspection by design team

FIGURE 1.18 Sequence of operations in design-bid-build (DBB) method of project delivery. Note that design and construction phases are in sequence, and GC is selected only after the construction documents have been completed by the design team.

Because of the prequalification established through bid bond, all bidders are similarly qualified with respect to financial ability, experience, and technical expertise. Because all bidders receive the same information and are of the same standing, the competition is fair. Therefore, the contract is generally awarded to a qualified bidder with the lowest bid amount.

DBB METHOD—COMPETITIVE SEALED PROPOSAL

This method is similar to competitive sealed bidding and is commonly used for publicly funded projects. The difference between competitive sealed bidding and competitive sealed proposal methods is that the owner's selection of the GC is not based on price alone but also on other criteria such as the GC's past experience, safety record, proposed personnel, and project schedule. To ensure fairness, the advertisement and bidding documents must provide the details of the selection criteria, with relative weightings assigned to each criterion.

DBB METHOD—INVITATIONAL BIDDING

Invitational bidding, also called *closed bidding*, is another variation of the DBB method that is generally used for quasi-public and some private projects. In this method, the owner preselects the GCs who have demonstrated, based on their experience, resources, and financial standing, their qualifications to perform the work. The selected GCs are then invited to bid for the project, and the GC with the lowest bid is then awarded the contract. The architect (as the owner's representative) may be involved in preselection process.

ADVANTAGES OF DBB METHOD

As stated in Section 1.9 and shown in Figure 1.14, the DBB method is the most popular method. In addition to being simple and well understood because of its long history, it has following advantages: (a) there is a single point of responsibility for construction, (b) the GC is selected through aggressive and open competition, and (c) the project's scope and cost are fully defined before construction starts.

1.14 PROJECT DELIVERY METHOD: DESIGN-NEGOTIATE-BUILD METHOD

A major disadvantage of the DBB method is the absence of the GC's preconstruction (design-phase) services. A delivery method that addresses this concern uses a negotiated contract and is called the *design-negotiate-build* (DNB) project delivery method.

The DNB method is used where the owner knows of one or more reputable, competent, and trusted GCs. The owner simply negotiates with them concerning the overall contract price, time required for completion, and other important details of the project. The negotiations are generally conducted with one GC at a time, and after negotiations with all selected GCs are complete, the owner analyzes the bids, selects a GC, and awards the contract.

A major advantage of the negotiated contract is that the GC can be on board during the design (or predesign) phase. This helps the owner ensure that the architect's design is realistically constructible. In many situations, the GC may advise the architect of simpler, less expensive, or more sophisticated building systems to realize the architect's design intentions.

Additionally, because the GC is the one who is most knowledgeable about construction costs, budget estimates can be obtained at various stages during the design phase. This means that value engineering can proceed throughout the design phase instead of being undertaken at the end of this phase or during construction, as in the DBB method of project delivery.

Because the vast majority of owners have to work within a limited budget, the DNB method is fairly popular for private projects. The services offered by the GC during the design phase of a negotiated contract are referred to as the GC's *preconstruction services*.

The negotiated contract is not devoid of competition, because the GC obtains competitive bids from numerous subcontractors and material suppliers. Because the GC is selected during the SD or DD stage, the bids from some or all subcontractors can be obtained earlier, which generally shortens the project delivery time.

1.15 PROJECT DELIVERY METHOD: CONSTRUCTION MANAGEMENT-RELATED METHODS

In the delivery methods so far discussed (DBB and DNB), the role of the architect remains essentially the same: the architect designs the project, helps the owner select the GC, and provides construction administration services during the construction phase as the owner's representative. In the 1970s, in response to cost overruns and time delays caused by lack of realism in the design of several projects, owners began to seek the assistance of the contracting community during the design phase of the project. This approach became more common as project complexities grew, giving birth to an entirely new profession called *construction management*.

CONSTRUCTION MANAGER AS THE OWNER'S AGENT— (CMAA) METHOD

The project delivery method, in which a construction manager (CM) is included, is referred to as the *construction manager as agent (CMAA) method*. In this method, the owner retains a CM as the owner's agent to advise on such issues as cost, scheduling, site supervision, site safety, construction finance administration, and overall building construction.

Note that the CM is not a GC, but a manager who plays no entrepreneurial role in the project (unlike the GC, who assumes financial risks in the project). In most CMAA projects, the owner hires the CM as the first step. The CM may advise the owner in the selection of the architect and other members of the design team as well as the contracting team.

The birth of the CMAA delivery method does not mean that there is no construction management in DBB, or the negotiated contract method. It exists but it is done informally and shared by the design team and the GC.

The introduction of a CM on the project transfers various functions of the GC (in a traditional method) to the CM. Thus, in the CMAA method, the GC becomes redundant. Therefore, there is no GC in this method, and the owner awards multiple contracts to various trade and specialty contractors, whose work is coordinated by the CM. Thus, the structural framework of the building may be erected by one contractor, masonry work done by another, interior drywall work by yet another, and so on.

Each contractor is referred to as a *prime contractor*, who may have one or more subcontractors, Figure 1.19. The task of scheduling and coordinating the work of all prime contractors and ensuring site safety—undertaken by the GC in the DBB and DNB methods—is done by the CM in the CMAA method. Additionally, the CM administers the contracts between the prime contractors and the owner. Note, however, that because the CM is only an agent (employed to administer the contract on behalf of the owner), all the financial risks and other liabilities in the project are assumed by the owner.

Thus, the owner, by assuming part of the role of the GC, eliminates the GC's markup on the work of the subcontractors. The owner may also receive a reduction in the fee charged by the architect for contract administration. Although these savings are partially offset by the fee that the owner pays to the CM, there can still be substantial savings in large but technically simple projects.

The CMAA project delivery method is particularly attractive to owners who are knowledgeable about the construction process and can participate fully in all of its aspects, from bidding and bid evaluation to the closeout phase.

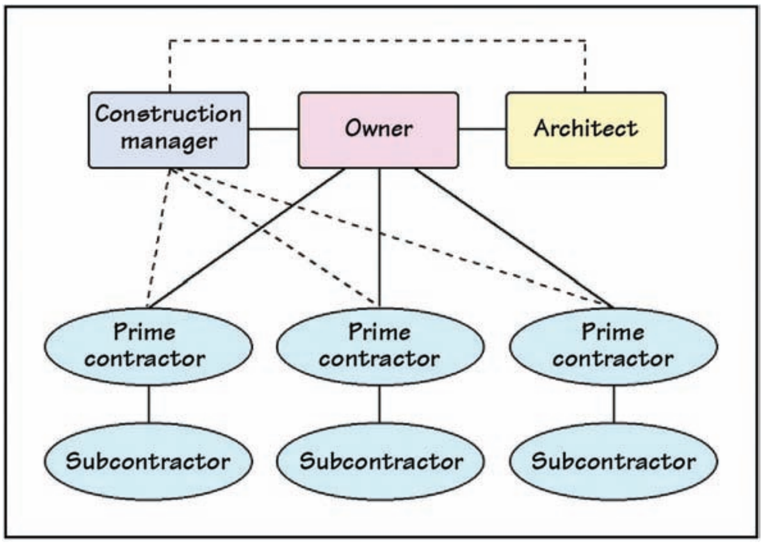


FIGURE 1.19 Contractual relationships between various parties in the CMAA method of project delivery. A solid line in this illustration indicates a contractual relationship between parties. A dashed line indicates a communication link, not a contract.

CONSTRUCTION MANAGER AT RISK (CMAR) METHOD

A disadvantage of the CMAA method lies in the liability risk that the owner assumes, which in the DBB method is held by the GC. This means that there is not the same incentive for the CM to optimize efficiency as when the CM carries financial risks.

Additionally, in the CMAA method, there is no single point of responsibility among the various prime contractors. Each prime contractor has a direct contract with the owner. Consequently, the CM has little leverage to ensure timely performance. The owner must therefore exercise care in selecting the CM because the cost, timeliness, and quality of the ultimate product are heavily dependent on the expertise of the CM.

In response to the preceding concerns, the CMAA method has evolved into what is known as the *construction manager at risk* (CMAR) method. In this method, the roles of the CM and GC are performed by one entity, but the compensation for these roles is paid separately by the owner.

In the CMAR method, the owner contracts with a CMAR company to (a) provide preconstruction services during the design phase of the project for a professional fee and (b) work as the GC of the project. Thus, the CMAR company works with the architect during the design phase to develop construction documents that will meet the owner's budget and schedule. In doing so, the CMAR company functions as the owner's representative. The relationships between the various parties in a CMAR project delivery method are shown in Figure 1.20.

After the drawings are completed, all the work is competitively bid by subcontractors and the bids are opened in the owner's presence. The work is normally awarded to subcontractors with the lowest bids. In working as the GC, the CMAR company assumes all responsibilities for subcontractors' work and site safety. The CMAR method is being increasingly used for publicly funded projects such as schools, university residence halls, and apartment buildings.

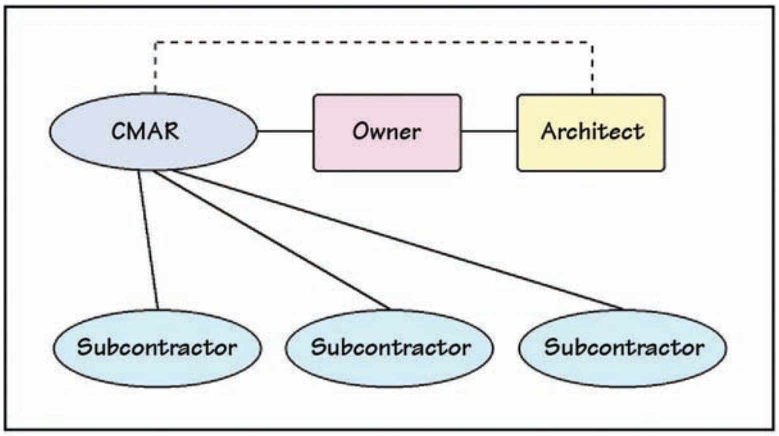


FIGURE 1.20 Contractual relationships between various parties in the CMAR method of project delivery. A solid line in this illustration indicates a contractual relationship between parties. A dashed line indicates a communication link, not a contract.

1.16 PROJECT DELIVERY METHOD: DESIGN-BUILD METHOD

A project delivery method that integrates design and construction activities into a single entity is called the *design-build (DB) method*. In this method, the owner awards the contract to one firm, which designs the project and also builds it, either on a cost-plus-profit basis or on a lump-sum basis. In many ways, this method resurrects the historic master-builder method, in which there was no separation between the architect and the contractor. The design-build firm is usually a GC, which in addition to providing construction capabilities, has a design team (of architects and engineers) within the organization, or a closely allied separate design firm.

The DB method has the advantage of integrating design and construction, thus fostering teamwork between the design team and the contracting team throughout the project. It can provide a reduction in change orders for the owner, faster project completion, and a single source of responsibility. The major disadvantage is that the owner does not receive the protection provided by the checks and balances inherent in delivery methods with separate design and construction responsibilities. Consequently, once the contract has been awarded to a DB firm, the owner loses much of the control over the project. Additionally, the architect does not represent the owner, as in other delivery methods. Therefore, for the DB method of delivery to succeed, the end result must be meticulously defined prior to the award of the contract.

The DB method has been in existence for decades in single-family residential construction. It is now being increasingly accepted in commercial construction—for both private and publicly funded projects. The establishment of the Design-Build Institute of America (DBIA) has further promoted the method.

A special version of DB method, referred to as the *turnkey method*, consists of the DB firm arranging for the land and financing for the project in addition to designing and constructing it.

1.17 INTEGRATED PROJECT DELIVERY METHOD

The integrated project delivery (IPD) method is the ultimate in promoting harmony, collaboration, and integration among all team members who contribute to the project. While the members of the triad (owner, architect-engineer team, and contracting team) are separated into three distinct entities in the DBB or CMAR method, and into two distinct entities in the DB method, they are integrated fully into one entity in the IPD method, Figure 1.21.

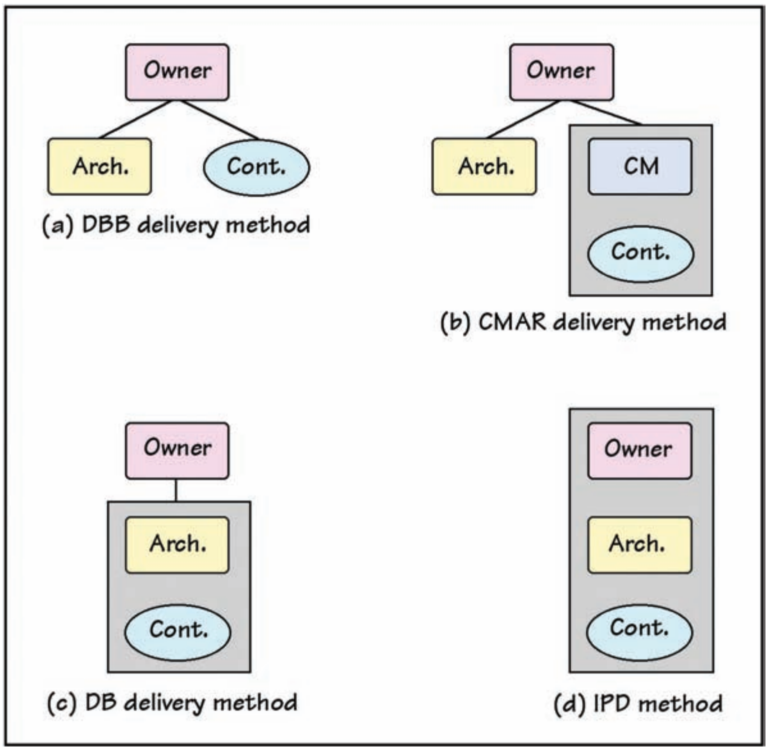


FIGURE 1.21 This illustration shows the relative integration among three major entities—owner, architect (Arch.), and contractor (Cont.)—in four major project delivery methods. Note that there is limited integration among the three entities in the DBB or CMAR method, partial integration in the DB method, and (supposedly) full integration in the IPD method. (The term *architect* implies the entire design team, which includes the architect and the architect's consultants.)

In fact, the IPD method involves not simply the integration of the three major entities but of all those who contribute to the project (owner, architect, engineers, GC, subcontractors, fabricators, material suppliers, etc.). All participants come on board during the design phase or as soon as their expertise is needed. The entire delivery process, from inception to completion, is open across participants, with continuous sharing of knowledge.

The central underlying philosophy of IPD is across-the-board, trust-based collaboration in a zero-blame and zero-litigation environment. Differences and disputes are resolved without delay, as in any well-run organization under a single command authority comprising a group of individuals representing different interests and expertise in the project. Therefore, the project's management is shared, and so are the responsibilities, risks, and rewards.

INTEGRATED PROJECT DELIVERY (IPD) AND BUILDING INFORMATION MODELING (BIM)

IPD can be used with traditional computer-aided design (CAD) technologies for design, preparation of construction documents, and actual construction and its management, but it is best suited for use with the latest technology known as *building information modeling* (BIM). Simply explained, BIM technology produces a virtual, three-dimensional model of the proposed building so that a complete digital version of the building is completed before its actual construction begins.

The virtual model is constructed through the participation and coordination of all members of the triad representing the owner, the architect-engineer team, and the contracting team, Figure 1.22. The model is built over a period of time in the same way that a real building is constructed. That is why the process using BIM is commonly referred to as *virtual construction*.

A virtual, three-dimensional model of the building is just one important feature of BIM. Another important feature is that the model contains information about the physical and performance characteristics of various components of the model—walls, floors, roofs, openings, finishes, and so on. Therefore, the model comprises intelligent, data-rich three-dimensional objects rather than mere two-dimensional graphics (lines, rectangles, curves, etc.).

BIM AND DETECTION OF CLASHES AMONG BUILDING COMPONENTS

The virtual construction feature of BIM ensures that the clashes between various building systems or components are discovered during the design phase and can be eliminated as the model is constructed. For example, because of the two-dimensional nature of conventional drafting technology, unintended but serious errors, such as an HVAC duct passing through a floor beam or an underground utility pipe crossing a column footing, are not uncommon

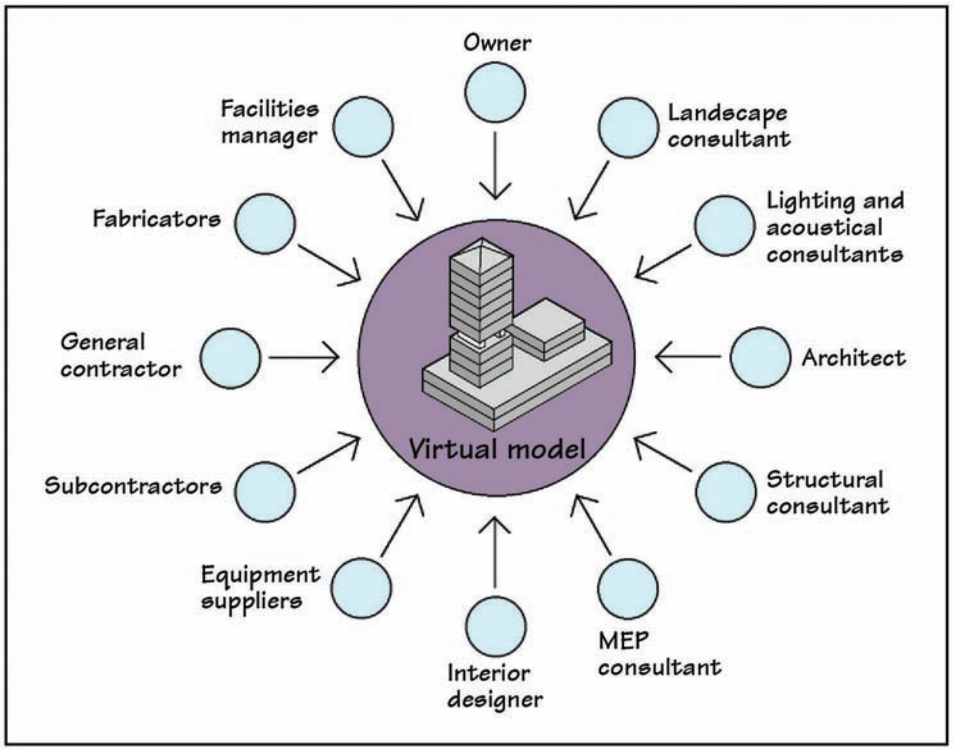
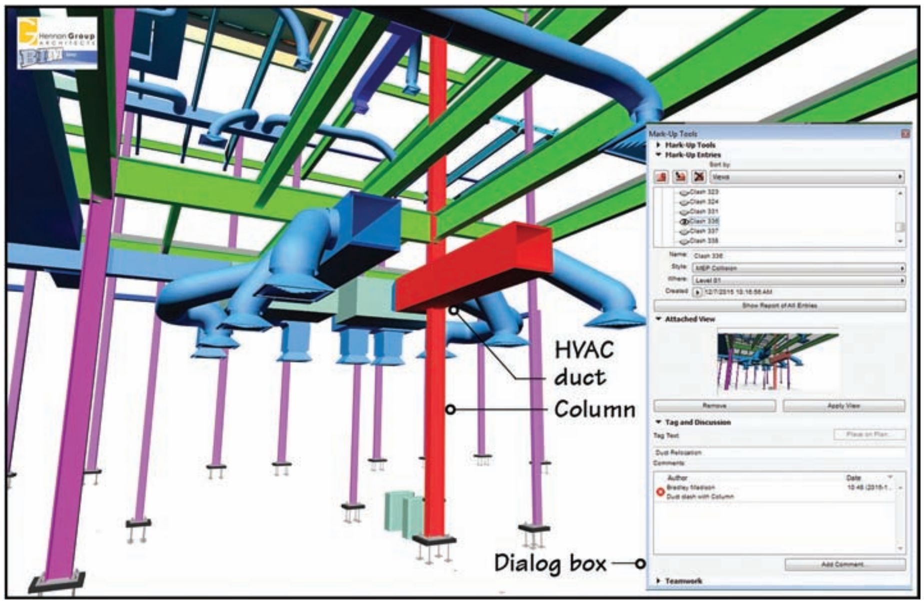


FIGURE 1.22 In an IPD method, all stakeholders in the project, such as the owner, architect, architect's consultants, general contractor, and subcontractors, contribute in constructing the virtual model.

in conventional projects. When discovered during construction, such errors result in a blame game, request for information (RFI) from the GC, change orders, increased project costs, and delayed project completion. In extreme cases, litigation is a possibility. BIM eliminates such possibilities. Figures 1.23(a) and 1.23(b) illustrate the capability of BIM for detecting clashes, such as between an HVAC duct and a column, and between a duct and two beams.

Error checking and ensuring compatibility among the works of various design and fabrication teams are revolutionizing project delivery because of BIM. Consequently, in some projects, there may be zero (or almost zero) change orders, providing substantial savings in project costs. Because the construction of the virtual model is comprehensive, the time needed to complete the sketch design (SD) and design development (DD) stages using BIM technology is greater than that using the conventional drafting technology. However, it is more than compensated by substantial reduction in the time needed for construction documentation because the model allows the extraction of two-dimensional construction documents (plans, elevations, sections, and specifications) with the press of a button, Figure 1.24.

The shift of time and effort toward design stages (SD and DD) from the documentation (CD) stage in BIM technology provides greater control over design. It also makes it easier to make design changes as compared with conventional technology because the cost of design changes during the CD stage is far greater than during SD and DD stages.


Hennon Group ARCHITECTS
BIM
HVAC duct
Column
Dialog box
Mark-Up Tools
Mark-Up Tools
Mark-Up Entries
Sort by
Views
Clash 323
Clash 324
Clash 331
Clash 336
Clash 337
Clash 338
Show Report of All Entries
Attached View
Remove
Apply View
Tag and Discussion
Place on Plan...
Add Comment...
Teamwork

Name: Clash 336
Style: MEP Collision
Where: Level 01
Created: 12/7/2015 10:16:56 AM
Tag Text: Duct Relocation
Comments:
Author: Bradley Madison
Date: 10:46 (2016-1...
Duct clash with Column

FIGURE 1.23(a) A screenshot from BIM model of a building showing the clash between a column and an HVAC duct. (Image courtesy of Hennon Group Architects and Graphisoft—the producer of ARCHICAD BIM software)

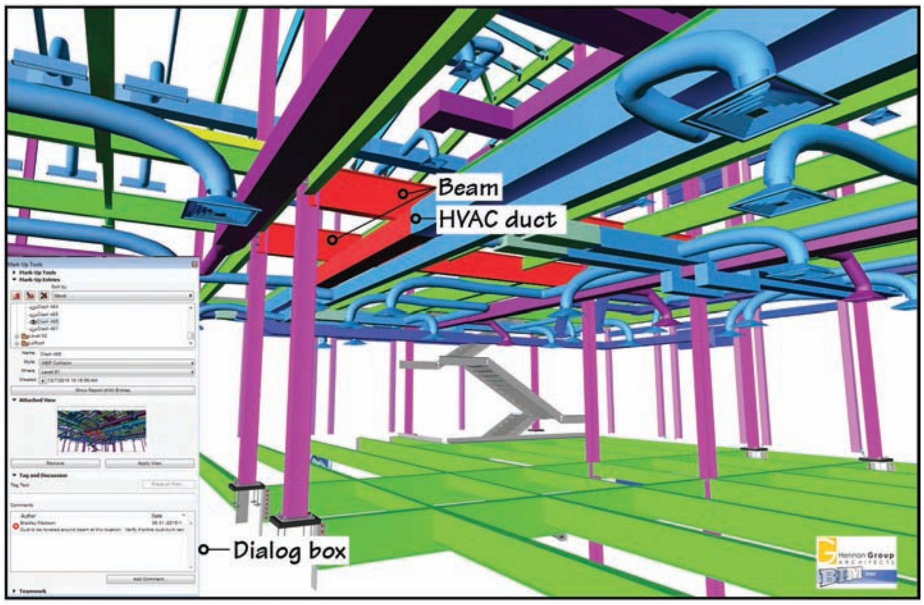

Beam
HVAC duct
Dialog box
Hennon Group ARCHITECTS
BIM
Mark-Up Tools
Mark-Up Tools
Mark-Up Entries
Show Report of All Entries
Attached View
Remove
Apply View
Tag and Discussion
Add Comment...
Teamwork

FIGURE 1.23(b) A screenshot showing the clashes between an HVAC duct and two beams. Note that the model for this image and that of Figure 1.23(a) highlights the clashing elements in red color. The dialog box in each image shows the image in miniature, the floor level where the clash occurs, and the identification mark of the clash to distinguish it from other clashes in the building. (Image courtesy of Hennon Group Architects and Graphisoft - the producer of ARCHICAD BIM software.)

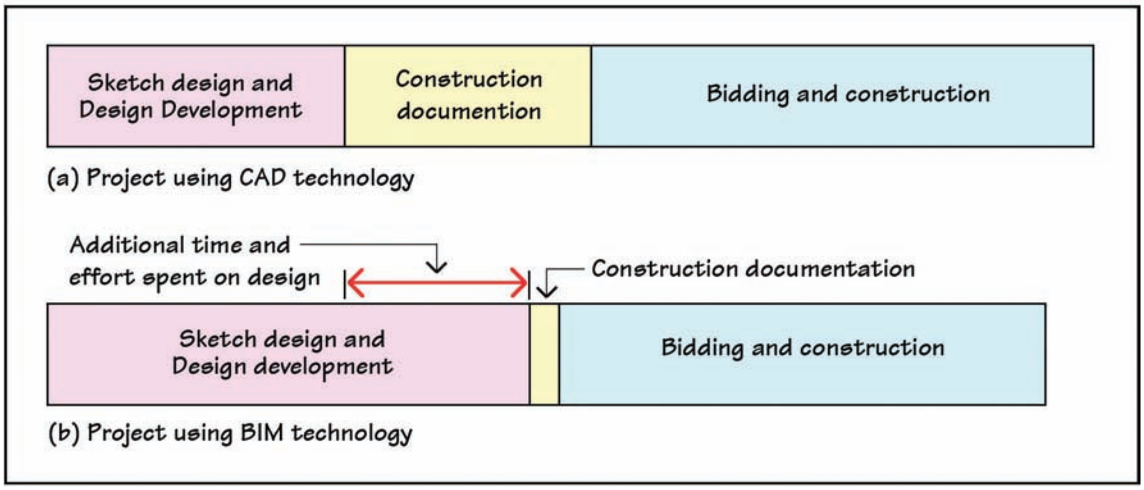

Sketch design and Design Development
Construction documention
Bidding and construction
(a) Project using CAD technology
Additional time and effort spent on design
Construction documentation
Sketch design and Design development
Bidding and construction
(b) Project using BIM technology

FIGURE 1.24 A comparison of the approximate overall time and effort spent in various activities in a project using CAD technology versus BIM technology.

BIM TOOLS AND INTEROPERABILITY

Various team members (shown in Figure 1.22) who contribute to the construction of the virtual model must use different software that are specific to their specialty. Thus, an architect uses architectural design BIM software to construct the model (e.g., Autodesk's Revit Architecture or Graphisoft's ArchiCAD BIM), a structural engineer uses structural analysis and design software (e.g., Autodesk's Revit Structure), and so on. These software tools are known as *BIM tools*. In order for a BIM tool to extract, process, and insert the information into the virtual model to update or modify it, it must be capable of providing seamless two-way communication with the model and other BIM tools.

The ability to exchange information between the virtual model and BIM tools is called *interoperability*. Interoperability implies that a software developed by a vendor as a BIM tool (say, a code analysis tool) is considered interoperable provided that it can be used correctly, completely, and easily with other BIM tools (such as BIM software for architectural design and for structural design).

LIFE-CYCLE NATURE OF BIM

The dynamic nature of BIM precludes the need to require record documents, as all changes made to the project during the design or construction phases are recorded in the model in real time. For the same reason, the model also serves as a maintenance tool for building users and facilities managers, providing a tool for record keeping throughout the life of the building, concerning factors such as life-cycle cost, energy use, and sustainability assessment.

Because BIM can track building performance, repairs, maintenance, and changes made to the building over its entire life, the owner's knowledge of and participation in virtual construction are critical. The same applies to architects and engineers, who will need to be more knowledgeable about building construction—how building assemblies go together—because they will be fully involved in the building's construction, albeit in the virtual environment.

BIM AND PRE-IPD DELIVERY METHODS

Although the development of BIM technology has helped the adoption of IPD, it should be noted that BIM is not limited to IPD but can be used with any project delivery method. Increasingly, a larger number of architecture and engineering firms are using BIM software with all types of delivery methods.

1.18 FAST-TRACK PROJECT SCHEDULING

A scheduling technique that can be used to save project delivery time with most project delivery methods is known as the *fast-track scheduling technique*. In this technique, the project is divided into multiple segments, and each segment of construction is awarded to different contractors through negotiations. The division of construction into segments is such that the segments are sequential. Thus, the first segment of the project may be site construction (site development, excavations, and foundations), the second segment may be structural framing (columns, beams, and floor and roof slabs), and the third segment may be the exterior enclosure, interior finishes, and project closeout that takes the project to completion.

Sequential segmenting of the project saves time because the earlier segments of the project can be constructed while the construction documents for the later segments are still in progress, resulting in overlapping design and construction processes, Figure 1.25.

Fast-track sequencing requires a great deal of coordination between segments. It also requires a commitment from the owner that the decisions will not be delayed and, once made, will not be changed.

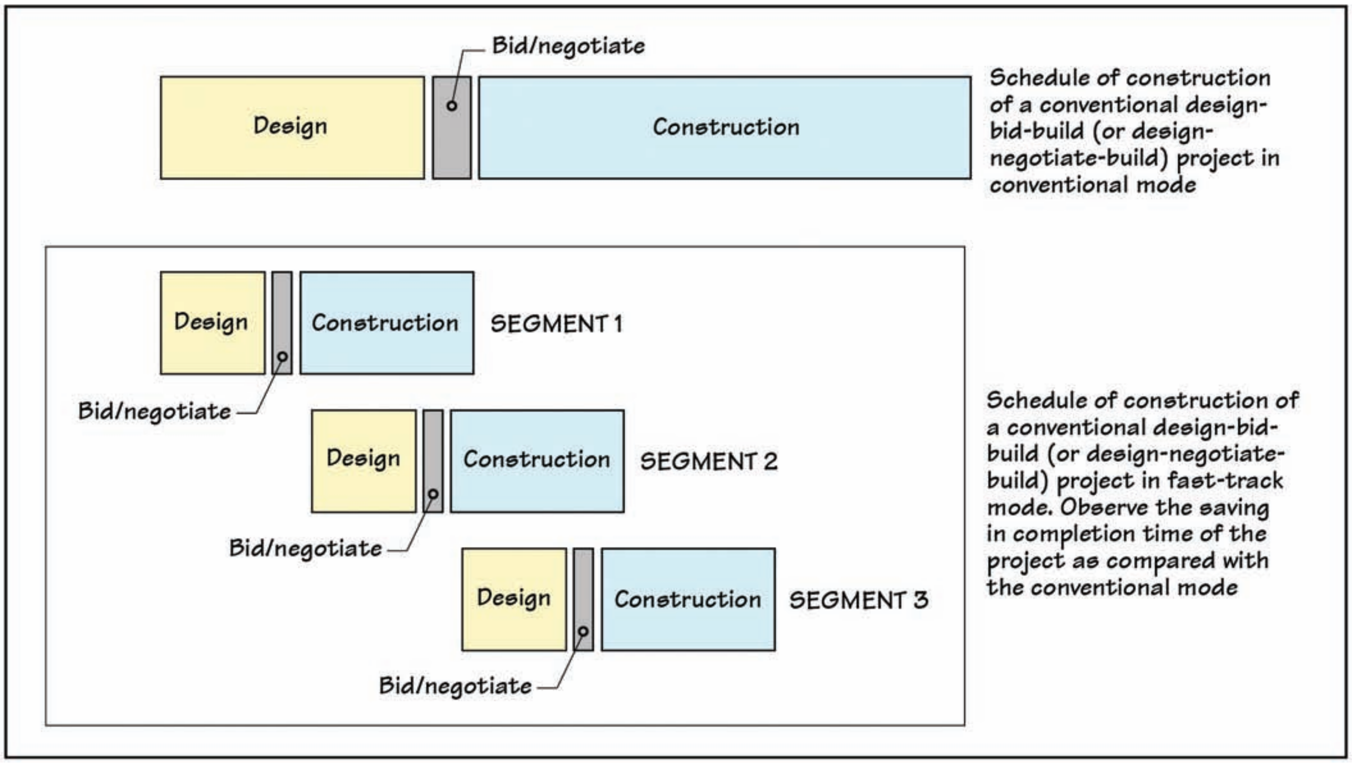

Bid/negotiate
Design
Construction
Schedule of construction of a conventional design-bid-build (or design-negotiate-build) project in conventional mode
Design
Construction
SEGMENT 1
Bid/negotiate
Design
Construction
SEGMENT 2
Bid/negotiate
Design
Construction
SEGMENT 3
Bid/negotiate
Schedule of construction of a conventional design-bid-build (or design-negotiate-build) project in fast-track mode. Observe the saving in completion time of the project as compared with the conventional mode

FIGURE 1.25 In fast-track scheduling, a project is segmented into parts, which overlap in time. As shown in this illustration, segmentation shortens project delivery in comparison with unsegmented scheduling. Fast-track scheduling is particularly suitable with DNB and CMAR project delivery methods because the GC is on board during the design phase.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

29. The shop drawings are prepared by the
- **a.** architect.
- **b.** structural engineer.
- **c.** MEP engineer.
- **d.** all of the above.
- **e.** none of the above.

30. Shop drawings are prepared during the design phase of the project.
- **a.** True
- **b.** False

31. The primary purpose of a mockup is to establish the quality of materials and workmanship involved in constructing important components of the building by which the completed components will be judged.
- **a.** True
- **b.** False

32. The day-to-day supervision of construction is the responsibility of the
- **a.** architect.
- **b.** architect's consultants.
- **c.** GC.
- **d.** collectively of all the above.

33. Who is typically responsible for obtaining the certificate of occupancy from the local jurisdiction?
- **a.** Architect
- **b.** Owner
- **c.** GC

34. The certificate of occupancy predates substantial completion inspection of the project.
- **a.** True
- **b.** False

35. The certificate of substantial completion is issued by the local jurisdiction.
- **a.** True
- **b.** False

36. The final completion inspection of the project is conducted by the
- **a.** architect.
- **b.** owner with the help of the architect.
- **c.** architect with the help of consultants.
- **d.** building official of the city.
- **e.** architect and the building official of the city.

37. The primary purpose of the contract modification procedure in the agreement between the owner and the GC is to allow change orders.
- **a.** True
- **b.** False

38. A record document set includes
- **a.** a record of all communications between the owner and the GC.
- **b.** a record of all communications among the owner, architect, and the GC.
- **c.** as-built construction drawings.
- **d.** as-built construction drawings, as-built specifications, as-built shop drawings, etc.
- **e.** none of the above.

39. When does the owner receive manufacturers' warranties from the GC?
- **a.** At substantial completion inspection
- **b.** At final completion inspection

(*Continued*)

- **c.** Within one week of the GC receiving warranties from the respective manufacturer or subcontractor
- **d.** None of the above

40. In which of the following project delivery methods, the GC provides preconstruction services?
- **a.** DBB Method: Competitive Sealed Bidding
- **b.** DBB Method: Competitive Sealed Proposal
- **c.** DBB Method: Invitational Bidding
- **d.** All of the above
- **e.** None of the above

41 In the CMAR method of project delivery, the CM
- **a.** advises the owner in the selection of the architect and the design team members.
- **b.** advises the design team with respect to the constructability of design decisions and their cost implications.
- **c.** works as the general contractor for the project.
- **d.** only (a) and (b).
- **e.** only (b) and (c).

42. The project delivery method in which only one firm is contracted for both design and construction of the building is called the
- **a.** design-bid-build method.
- **b.** design-build method.
- **c.** CMAA method.
- **d.** CMAR method.
- **e.** IPD method.

43. The project delivery method that should ensure the least amount of litigation among parties contributing to the project is the
- **a.** design-bid-build method.
- **b.** design-build method.
- **c.** CMAA method.
- **d.** CMAR method.
- **e.** IPD method.

44. BIM is the most recently developed project delivery method.
- **a.** True
- **b.** False

REVIEW QUESTIONS

1. List the phases into which the work on a building project is divided, including the three subdivisions (stages) of the design phase. Then, briefly explain what is accomplished in each stage.
2. Using a diagram, show the contractual relationships among the owner, architect, consultants, GC, and the subcontractors in a conventional (design-bid-build) building project.
3. Sketch in three dimensions the hypothetical building given in the text, which may be used to recollect the first 10 divisions of the MasterFormat. Then, list these 10 divisions.
4. List the important items contained in a project manual. At what stage are addenda and contract modifications added to the document that will finally become the project manual?
5. Using a sketch, explain the difference among construction documents, bidding documents, and contract documents.
6. Explain the difference between change orders and contract modifications.
7. Explain what is included in record documents and why they are required.
8. What are shop drawings, why are they required, and for which items? Who prepares them and do they require any approval? If so, by whom? Explain.
9. Explain the purposes of the three surety bonds used in a typical building project, and the stages at which they are provided.
10. Provide the spelled-out versions of the acronyms “CMAA” and “CMAR”. Then, explain the differences between the two project delivery methods. Use sketches to illustrate the contractual relationships between various parties involved in both methods.
11. Explain the benefits of the GC’s preconstruction services. In which project delivery methods are GC’s preconstruction services available?
12. Explain what is integrated project delivery and how it differs from the other methods of project delivery.
13. Using a sketch, explain what fast-track scheduling is, and then, list its advantages and disadvantages.

PROJECT DELIVERY METHODS AT A GLANCE

Project Delivery Method	Description
Design-Bid-Build (DBB) Delivery (Competitive Sealed Bids)	The oldest and most familiar project delivery method. Construction work is awarded to the general contractor (GC) with the lowest bid through open aggressive bidding. There is no design-phase assistance from the GC, and hence a lack of coordination between the design and construction processes. The exact price is unknown until bidding process is complete. Commonly used for public projects.
Design-Bid-Build (DBB) Delivery (Competitive Sealed Proposals)	Same as the DBB (competitive sealed bid) method, except that the owner’s selection of the GC is based not only on cost but also on several other criteria such as the project schedule, safety record, and qualifications of the GC’s personnel. Commonly used for public projects.

(continued)

Project Delivery Method	Description
Design-Bid-Build (DBB) Delivery (Invitational Bidding)	Same as the above two methods, except that the competition is not open, but limited to those GCs who are preselected by the owner and invited to bid. The GC with the lowest bid is generally awarded the contract. Commonly used for private or quasi-private projects.
Design-Negotiate-Build (DNB) Delivery	Same as the DBB (invitational bidding) method, except that the competition among GCs is limited to those who are preselected by the owner. Negotiations are conducted early during the design phase with one GC at a time. The GC who provides the best value for money is awarded the contract, who also provides design-phase assistance. Commonly used for private or quasi-private projects.
Construction Manager as Agent (CMAA) Delivery	The owner hires a construction manager (CM) as his or her agent (instead of the architect), who provides design-phase assistance to the architect and also performs several functions of the GC, such as construction scheduling, coordination, and site safety. There is no GC in this method, and the work is awarded to several subcontractors (called prime contractors) under contracts with the owner. The CM is paid a fee and carries no financial risk or legal responsibility for the prime contactors' work. Commonly used for projects when the owner is experienced in contract administration.
Construction Manager at Risk (CMAR) Delivery	In this method, which has largely replaced the CMAA method, the CM performs two sequential roles. In the first role, the CM works as the owner's representative and provides design-phase assistance to the architect. For this role, the CM is paid a fee. In the second role, the CM functions as the GC after the completion of the design phase, and is compensated under a conventional owner-contractor agreement with all attendant risk and liability; hence, the CM is called CMAR. The CMAR obtains competitive bids from subcontractors, as in a DBB method. Used for both private and public projects.
Design-Build (DB) Delivery	In all previous methods, there is a lack of collaborative relationship between the design and construction teams—a lack that is addressed in this method because both design and construction work are awarded to one firm, called a design-build firm. The method generally saves time and cost to the owner, but to be successful, the owner's program must be precisely defined at the beginning of the project. Used for both private and public projects.
Integrated Project Delivery (IPD)	This method, which is still evolving, differs substantially from all other methods. It requires complete collaboration among the owner, architect, and GC in a zero-blame and zero-litigation environment. For successful integrated delivery, a virtual model of the project is constructed (using building information modeling, BIM) during the design phase with collaboration from all parties—owner, architect, consultants, GC, subcontractors, fabricators, material suppliers, so on.

CHAPTER 2

Design and Construction Regulations

CHAPTER OUTLINE

2.1 OBJECTIVES OF A BUILDING CODE—HEALTH, SAFETY, AND WELFARE (HSW)

2.2 ENFORCEMENT OF A BUILDING CODE

2.3 PRESCRIPTIVE AND PERFORMANCE CODES

2.4 MODEL CODES

2.5 CONTENTS OF A BUILDING CODE

2.6 APPLICATION OF A BUILDING CODE

2.7 OCCUPANCY CLASSIFICATION OF A BUILDING

2.8 TYPE OF CONSTRUCTION CLASSIFICATION OF A BUILDING

2.9 CONSTRUCTION STANDARDS

2.10 STANDARDS WRITING ORGANIZATIONS

2.11 OTHER MAJOR REGULATORY CONSTRAINTS

2.12 ZONING ORDINANCE

2.13 BUILDING'S ACCESSIBILITY—AMERICANS WITH DISABILITIES ACT (ADA)

PRINCIPLES IN PRACTICE: BUILDING CODE ANALYSIS—A PART OF CONSTRUCTION DOCUMENTS

The primary requirement of a building is that it should be safe and healthy. Visual appeal and economic viability, though important, are secondary requirements. To deliver a safe and healthy building is primarily the responsibility of the design and construction professionals—architects, engineers, and builders. However, as with all public health and safety issues, the design and construction of buildings are regulated by numerous federal, state, and local laws. The most important of these laws are contained in a document called the *building code.*

A building code is enforced by local jurisdictions, such as cities or municipalities, under police powers granted to them by the state. No building may be constructed unless it meets the requirements of the building code of the local jurisdiction.*

Although a few building code provisions are based on traditional construction practices, most provisions are firmly grounded in scientific and quantifiable data of construction performance. There is, therefore, a strong link between code requirements and the science of construction.

Ongoing technological developments in the building industry require that building codes be constantly reviewed and revised. This task is usually beyond the resources of most local jurisdictions. It is, therefore, handled by an independent agency—the model code organization—whose primary responsibility is to develop, maintain, and publish the building code and the other related codes.

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* There are often unregulated areas in a state or county where buildings may be constructed without conforming to any building code. Rural communities and areas outside urban boundaries are generally unregulated.

This chapter begins with a discussion of the objectives of a building code, followed by a description of the organizational principles and contents of the current model building code. Finally, the chapter deals with zoning ordinances and other important laws that affect building construction.

2.1 OBJECTIVES OF A BUILDING CODE—HEALTH, SAFETY, AND WELFARE (HSW)

The objectives of a building code are to ensure that all new construction and renovated buildings provide a minimum level of health, safety, and welfare (HSW) to the occupants and the public at large. Although under no legal obligation to do so, the owner or the designer may choose to exceed the requirements of the code. For the sake of economy, however, a large majority of buildings are designed to satisfy only the minimum requirements.

A building code does not regulate aspects of design that relate to a building's appearance. It deals with the issues of a building's performance. Therefore, aesthetics, color, and form-related attributes are outside the purview of building codes. The zoning ordinance of a jurisdiction (city), covered later in this chapter, may however regulate aesthetic aspects of building design.

Additionally, the code protects the health, safety, and welfare not only of the owner of the project but also of the general public, because the interests of the owner, the general public, and the building occupants may be at variance with one another. What may be in the best interest of the owner may not be in the best interest of the public or the occupants of the building.

For this reason, building construction is regulated by an impartial authority, such as the state, county, or city. It is the responsibility of the regulatory authority to ensure that the interests of all concerned parties are protected. Although design and construction professionals generally dislike having their work policed by an external authority, building codes have one major benefit for them all—that of liability protection. If the building has been designed and constructed in accordance with the building code and other applicable regulations, the design and construction professionals are exposed to a substantially lower liability risk.

In more specific terms, a building code regulates the following aspects of building design and construction:

- Life safety
- Fire and smoke safety
- Structural safety
- Health and welfare (including natural resource conservation)
- Property protection

LIFE SAFETY

Although both fire safety and structural safety are essentially life safety issues, the reverse is not always true. The term *life safety* has its own independent existence in building codes, because several safety regulations in codes are related neither to fire safety nor structural safety. For example, a guardrail on a balcony, apart from being structurally adequate, must provide protection from the danger of falling over the top of the rail or from between its vertical or horizontal members, Figure 2.1.

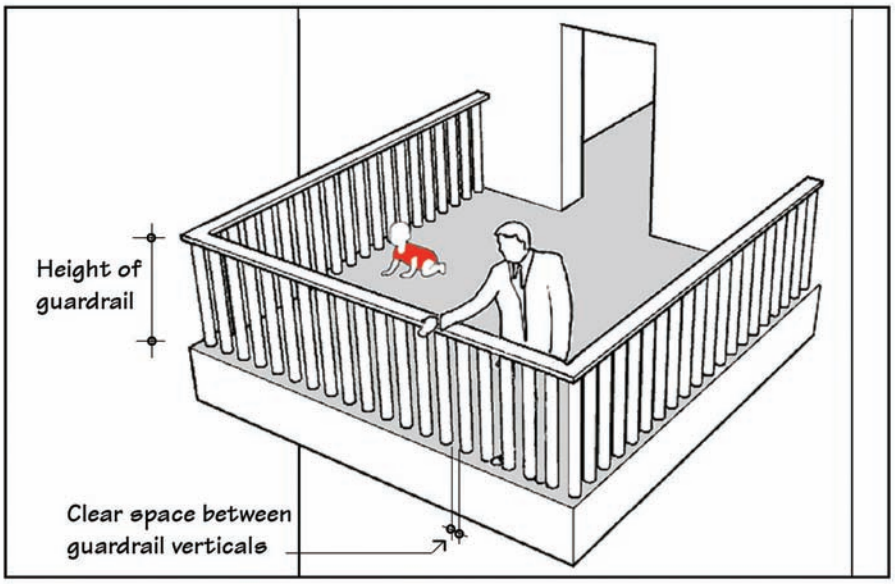

Height of guardrail
Clear space between guardrail verticals

FIGURE 2.1 In addition to its structural integrity, the height of a guardrail is regulated by the building codes to ensure safety against an adult falling over the guardrail. Similarly, the clear spaces between the guardrail's vertical support members (balusters) are regulated to prevent an infant crawling through.

Thus, the regulations relating to the height of a guardrail and the clear space between its members are life safety regulations with no relationship to fire safety or structural safety. Similarly, the handrail on a staircase, apart from being structurally strong, must provide adequate grippage. A handrail whose cross section is either too large or too small will not provide the required safety. Therefore, building codes prescribe maximum and minimum dimensions of a handrail in addition to its clearance from the adjacent wall, Figure 2.2. These regulations are life safety regulations, as distinct from structural safety and fire safety regulations. Similarly, the relationship between the treads and risers of a staircase, the dimensional uniformity of the treads and risers, and the slope of a ramp are some other examples of life safety issues in codes, Figure 2.3.

Additionally, code regulations related to accessibility into building spaces for the physically challenged among us are life safety regulations. Note that the physical challenge may not just relate to mobility as is widely thought but also to size (e.g., children), age, vision, hearing, and so on. Accessibility, an important topic, is covered very briefly in Section 2.13.

FIRE AND SMOKE SAFETY

Fire safety regulations in building codes are among the most important regulations. If one were to separate structural regulations from building codes, the bulk of the remaining regulations would relate, in one way or another, to fire safety issues. In fact, the history of building codes is replete with instances in which the world's prominent cities either promulgated building codes for the first time or drastically revised their existing ones after the outbreak of major fires, Figure 2.4.

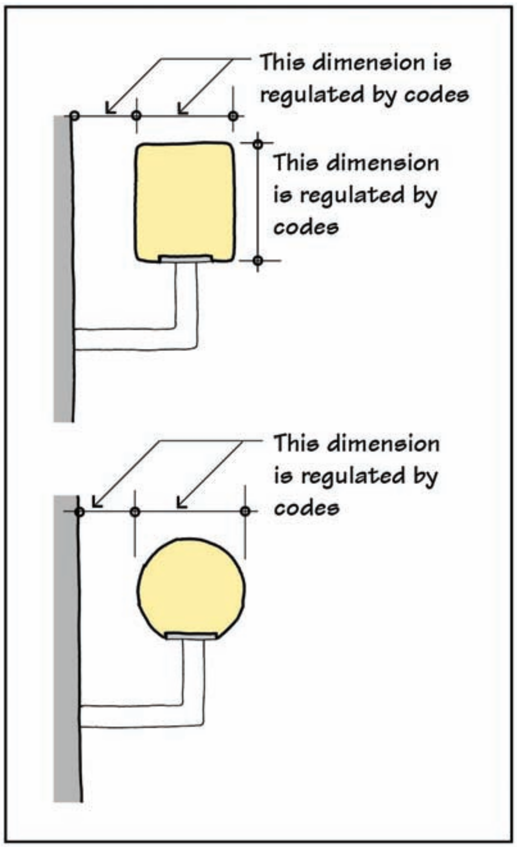

This dimension is regulated by codes
This dimension is regulated by codes
This dimension is regulated by codes

FIGURE 2.2 To ensure adequate grippage, the building code regulates various dimensions of the handrail of a stair.

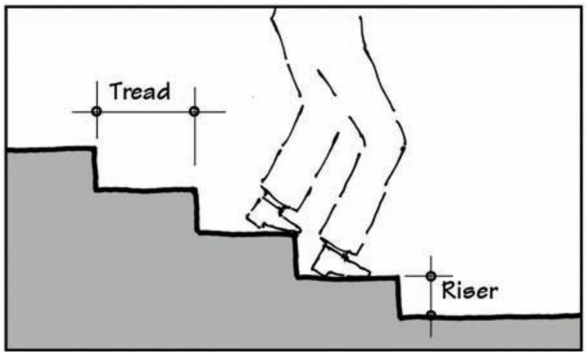


FIGURE 2.3 The dimensions of the treads and risers of a stair are regulated by the codes. Additionally, each tread must be of the same dimension and profile. The same applies to the risers, see Section 35.1.

64 A.D. THE BURNING OF ROME
Some historians believe that it was Emperor Nero who had Rome burned. The city was rebuilt mainly with noncombustible materials and under stricter building regulations.

GREAT FIRE OF LONDON OF 1666
In 1667, the British Parliament passed a law to rebuild London with several new and more stringent building regulations.

BALTIMORE FIRE OF 1858
Baltimore established its first building code in 1859.

CHICAGO FIRE OF 1871
Chicago established its first building code in 1875.

FIRST U.S. BUILDING CODE 1905
The first model building code in the United States was published by an insurance group that insured buildings against fire damage—the National Board of Fire Underwriters. This code was later renamed as the National Building Code.

FIGURE 2.4 A few important dates that underline the importance of fire safety in building code development.

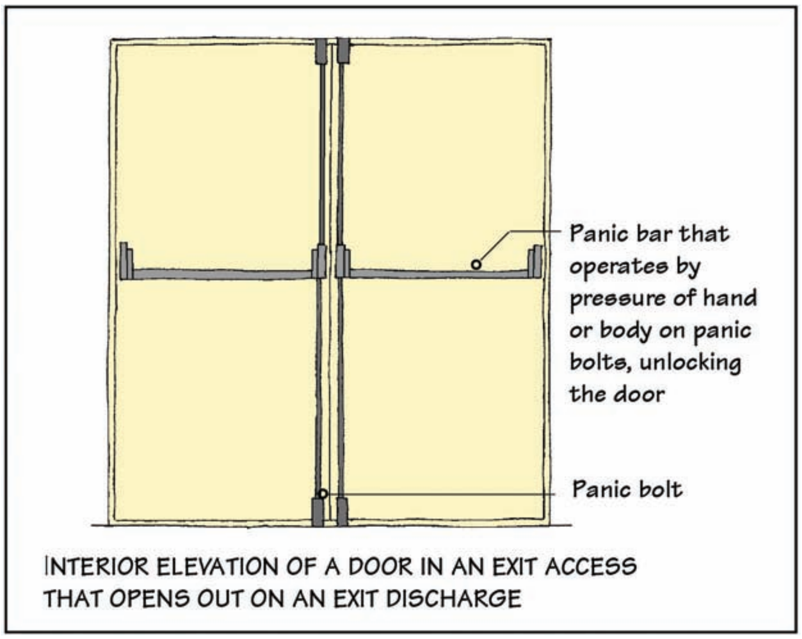

Panic bar that operates by pressure of hand or body on panic bolts, unlocking the door
Panic bolt
INTERIOR ELEVATION OF A DOOR IN AN EXIT ACCESS THAT OPENS OUT ON AN EXIT DISCHARGE

FIGURE 2.5 Panic hardware on an exit door (in a means-of-egress system) is regulated by codes to ensure fire safety in buildings.

Obviously, fire safety regulations relate to the use of fire-resistant building assemblies. As we will see in Chapter 7, the types of building construction, as defined by the codes, are directly related to the fire resistance of the major components of the building—walls, floor, roofs, beams, columns, and so on. We will also observe in that chapter that smoke plays a predominant role in the safety of occupants during a fire. Therefore, fire safety regulations are, in fact, fire and smoke safety regulations.

The regulations governing the provision of fire and smoke detection, such as fire and smoke alarms, fire suppression, fire-extinguishing systems (automatic sprinklers and standpipes), and so on, are parts of the fire safety regulations. Similarly, the regulations for exit doors, including their height, width, fire resistance, panic hardware, and direction of swing are all part of fire safety considerations, Figure 2.5.

MEANS-OF-EGRESS SYSTEM—AN IMPORTANT PART OF FIRE AND SMOKE SAFETY

One of the most important sets of fire and smoke safety regulations deals with the means of egress from the building (escape routes) should a fire occur. A means of egress in a building is a system that consists of the travel route taken by a building occupant to escape from the interior of the building to a public way. The route, which must remain unobstructed at all times, passes from an occupied space through the following three elements: (a) exit access, (b) exit, and (c) exit discharge, Figure 2.6.

Exit Access: An exit access is an interior space that leads to an exit. Thus, a corridor leading from a room to an exterior door at the ground level or to an exit staircase (that has an exterior door opening at the ground level) is an exit access. Note that a room or other interior space is also part of the exit access.

Exit: An exit lies between the exit access and exit discharge. It may be an exterior door at the ground level, an enclosed staircase, or an enclosed ramp that opens at the ground level. The enclosure of the stair or ramp must provide a higher degree of fire protection than in exit access. That is why, while the maximum length of travel from the remotest point in an occupied space up to the exit (exit door or the entry point of an exit stair) is controlled by the codes, the travel length through an exit stair is not controlled, Figure 2.7.

Exit Discharge: An exit discharge is an exterior or interior space immediately beyond the exit at the ground level that leads to a public way. It may be a courtyard, plaza, or any other open-air space adjoining an exit door. An exterior door is an exit only if it opens onto an exit discharge. An exterior door opening into an open-air courtyard that is closed on all sides is not an exit. A portico or an open verandah at the ground floor that connects an enclosed staircase to the street is also an exit discharge.

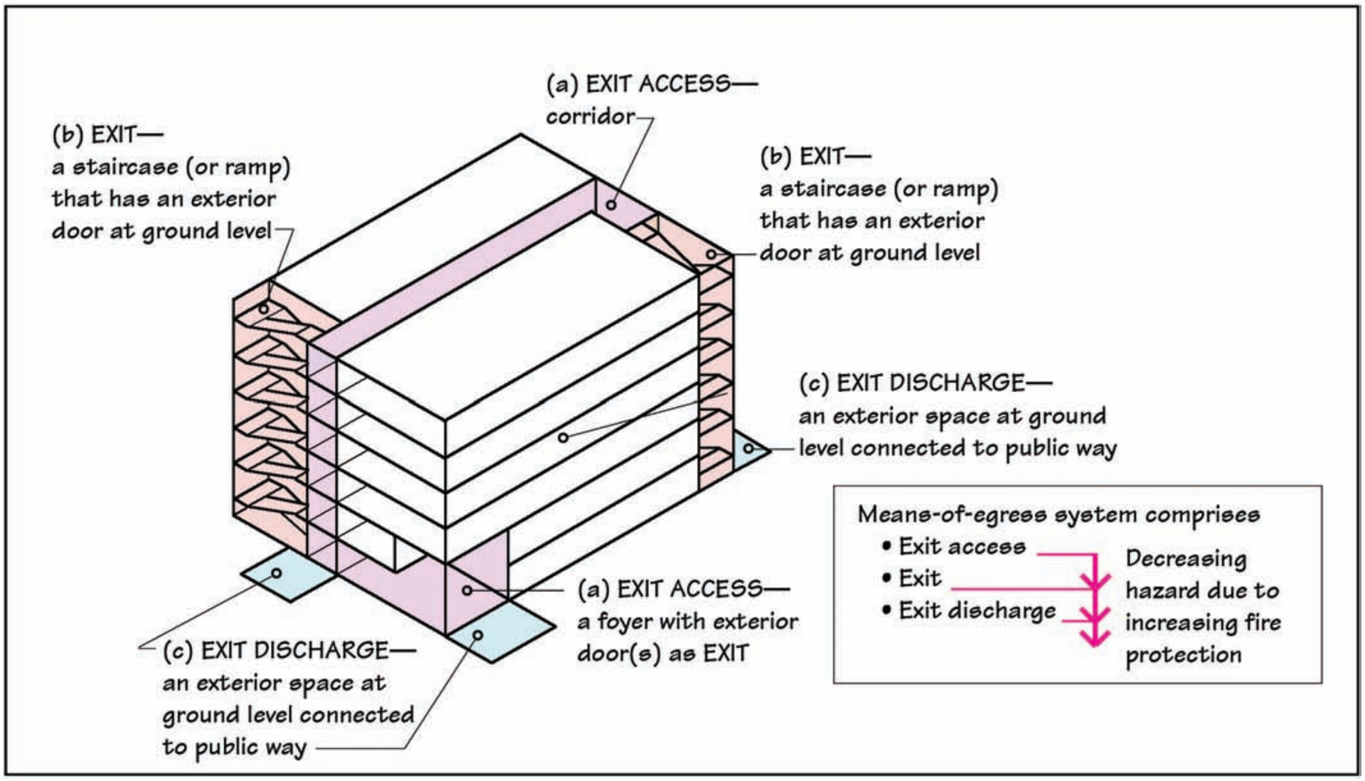

(a) EXIT ACCESS—
corridor
(b) EXIT—
a staircase (or ramp)
that has an exterior
door at ground level
(b) EXIT—
a staircase (or ramp)
that has an exterior
door at ground level
(c) EXIT DISCHARGE—
an exterior space at ground
level connected to public way
Means-of-egress system comprises
• Exit access
• Exit
• Exit discharge
Decreasing
hazard due to
increasing fire
protection
(a) EXIT ACCESS—
a foyer with exterior
door(s) as EXIT
(c) EXIT DISCHARGE—
an exterior space at
ground level connected
to public way

FIGURE 2.6 The means-of-egress in a building is a system that consists of three components: **(a)** exit access, **(b)** exit, and **(c)** exit discharge. A corridor is an example of an exit access. A staircase (or ramp) with a door at the ground floor that provides an access to an excess discharge is an exit. An exit discharge is an exterior space at ground level that is accessible to a public way.

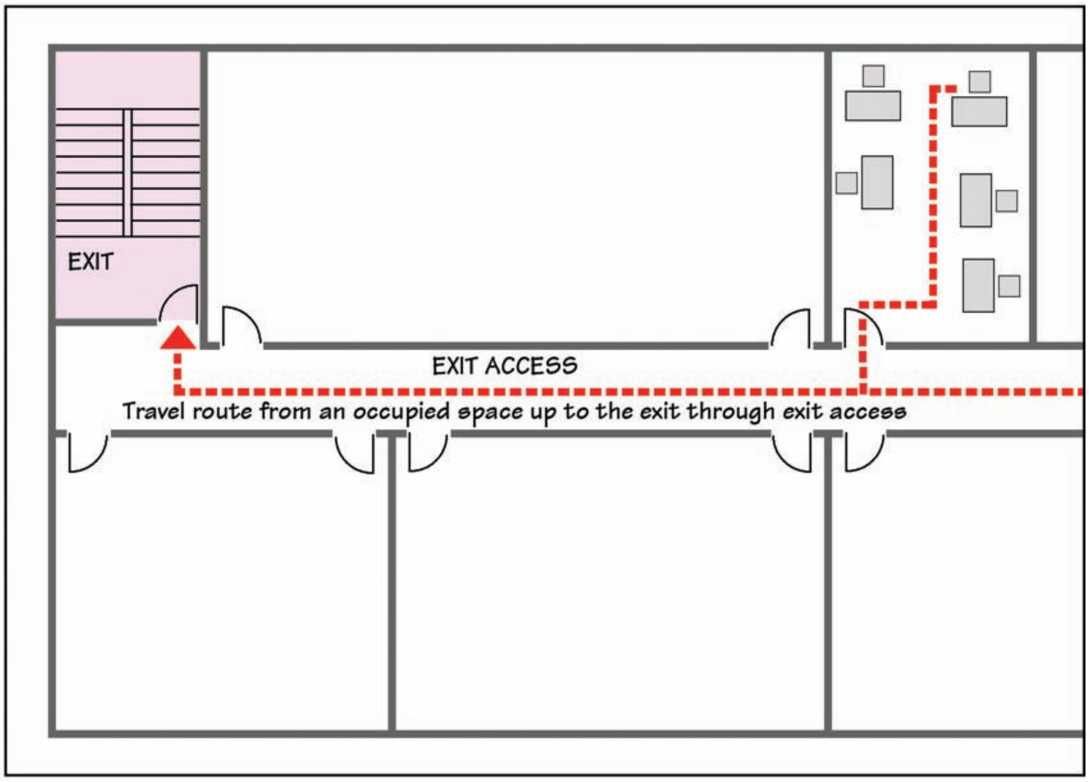

EXIT
EXIT ACCESS
Travel route from an occupied space up to the exit through exit access

FIGURE 2.7 The maximum length of travel route from the remotest point in an occupied space up to the entry point of an exit stair is controlled by the building codes. The length is a function of occupancy and whether the building is sprinklered or not. The length of travel within the exit stair is not controlled.

STRUCTURAL SAFETY

Structural safety is obviously one of the primary objectives of a building code. A building code contains several chapters that provide detailed regulations dealing with the structural design of buildings. As stated previously, structural regulations are the most numerous and account for the largest volume of the building code document.

HEALTH AND WELFARE (INCLUDING NATURAL RESOURCE CONSERVATION)

Although the main preoccupation of a building code is with traditional concerns of life safety, fire safety, and structural safety, it also deals with human health and welfare issues. Therefore, the building code contains provisions related to interior and exterior lighting, ventilation, sanitation, temperature, and noise control. For the same reasons, the minimum dimensions of habitable rooms are regulated by the codes.

Regulations pertaining to natural resource conservation (energy conservation, water conservation, soil erosion control, and so on) are also part of health and welfare provisions of the code. The importance of resource conservation in building codes is highlighted through two separate code publications—one for energy conservation (see Chapter 5) and the other for sustainable construction (see Figure 2.15 and Chapter 10).

PROPERTY PROTECTION

Safeguarding a building against loss or damage (property protection) is indirectly ensured through life safety and fire safety regulations, because the burning of the building or its structural collapse are two major causes of property damage. However, the codes also contain several regulations that deal with property protection through requirements for the durability of building assemblies.

These durability regulations are embedded in the codes through materials and construction standards (see Sections 2.9 and 2.10) to which the codes refer. For instance, the codes require that roof membranes and many other materials conform to relevant ASTM specifications. These specifications contain requirements for the durability of materials. Several other durability requirements, such as those for the destruction of wood from termite and fungal attack, degeneration of materials due to freeze-thaw action, and corrosion of metals, are expressly stated in the codes.

2.2 ENFORCEMENT OF A BUILDING CODE

A building code is a legal document enforced through the police powers of the state. It is under these powers that a state is authorized to enact legislation for the safety of its citizens. The health, traffic safety, and general welfare of the public are also promoted by the state under the same legislation.

Because it is generally agreed that the construction of buildings and the development of neighborhoods are best left under the direct control of local citizens, the state usually delegates this power to local (city or county) governments. Thus, it is under the police powers delegated to them by the state legislature that local jurisdictions are able to enact, adopt, review, or change a provision of the building code, subject to any overriding state or federal legislation.

BUILDING OFFICIAL—THE OFFICIAL-IN-CHARGE OF THE DEPARTMENT OF BUILDING SAFETY

The local jurisdiction's authority to enforce and administer the code is exercised through an enforcement official, called the *building official* or the code official, who is an employee of the jurisdiction and the official-in-charge of the jurisdiction's department of building safety. Because the building official's authority stems from the police powers of the state, a building official has the powers of a law enforcement officer.

It is the responsibility of the building official to verify that buildings constructed in the jurisdiction are safe and comply with the provisions and the intent of the code. It is the building official's duty to prevent and/or take action to correct any violation of the code.

According to one authority [Ref. 2.1], "A building official . . . is a highly specialized law enforcement officer whose prime mission is the prevention, correction, or abatement of violations . . . . A building official designs nothing, builds nothing, and repairs nothing. His responsibility is merely to see that those persons who are engaged in these activities do so within the requirements of the law."

In order to effectively discharge duties, a building official must have a thorough knowledge of the building codes, related city regulations, and the science of building construction. Law enforcement responsibilities require that a building official's dealings with the public be fair and impartial.

As the head of a city's department of building safety, the building official is usually assisted by several other functionaries (plans examiners and building inspectors) to carry out such tasks as plan reviews and field inspections. In a small city or jurisdiction, the building official may be the only person performing these tasks. Some cities (particularly smaller cities) may outsource some or all of a building official's functions to an outside consultant—a noncity employee.

NOTE

Alternative Titles for the Building Official

Some jurisdictions call the building code enforcement official the *director of the department of building safety* or *manager of building safety*. Some very small jurisdictions may have a part-time employee to enforce the codes and may designate that person as the *building inspector*.

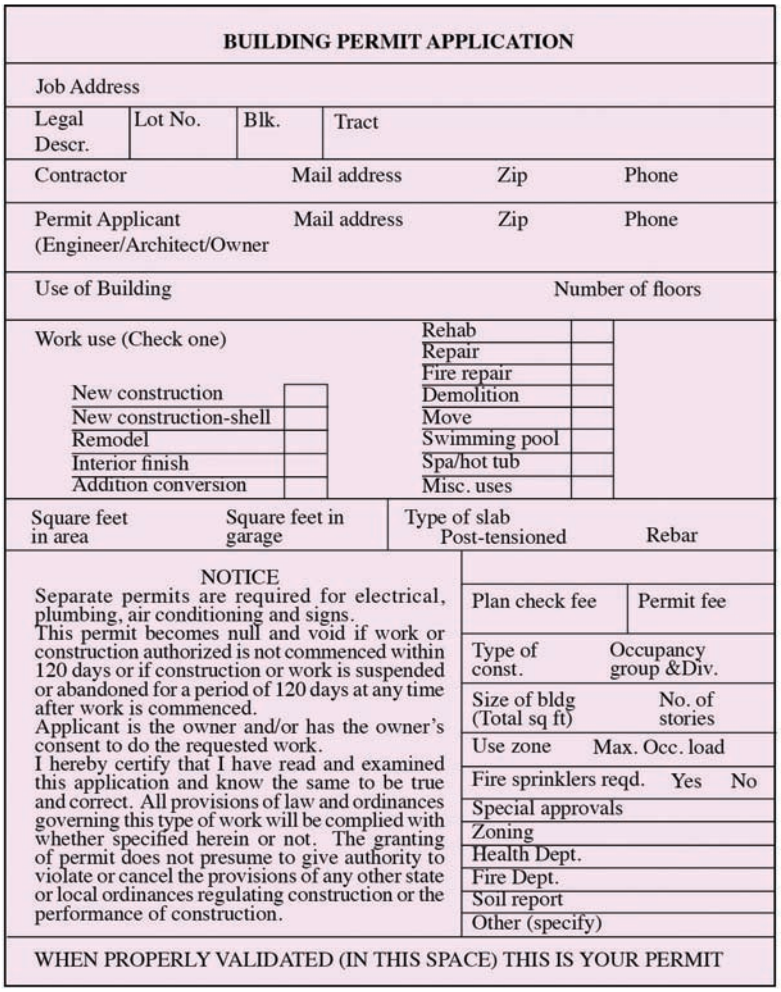
BUILDING PERMIT AND CONSTRUCTION DOCUMENT SET

The general procedure followed in administering the code is to require that the design of a proposed building complies with the provisions of the code before official permission to commence construction is granted by the jurisdiction. Before granting approval for construction in the form of a *building permit*, the city requires the submission of:

- Building permit application.
- Required fee, generally based on the estimated cost of the project per the city's guidelines.
- At least two copies of the construction document (CD) set for the proposed building, or a digital CD set if acceptable to the jurisdiction.

A typical building permit application form is shown in Figure 2.8.

If the CD set is in accordance with the building code and other applicable laws, the building permit and one copy of the CD set (with the jurisdiction's stamp of approval) is returned to the owner (or the owner's designated agent). After receiving them, the owner may commence construction, and must make available the building permit and the approved CD set at the construction site at all times. If the CD set does not comply, the owner is notified by the building official, and the CD set must be revised and resubmitted to the city until conformance with the code is achieved.



BUILDING PERMIT APPLICATION

Job Address

Legal Descr. | Lot No. | Blk. | Tract

Contractor | Mail address | Zip | Phone

Permit Applicant (Engineer/Architect/Owner) | Mail address | Zip | Phone

Use of Building | Number of floors

Work use (Check one)

New construction ☐
New construction-shell ☐
Remodel ☐
Interior finish ☐
Addition conversion ☐

Rehab ☐
Repair ☐
Fire repair ☐
Demolition ☐
Move ☐
Swimming pool ☐
Spa/hot tub ☐
Misc. uses ☐

Square feet in area | Square feet in garage | Type of slab Post-tensioned Rebar

NOTICE

Separate permits are required for electrical, plumbing, air conditioning and signs.
This permit becomes null and void if work or construction authorized is not commenced within 120 days or if construction or work is suspended or abandoned for a period of 120 days at any time after work is commenced.
Applicant is the owner and/or has the owner's consent to do the requested work.
I hereby certify that I have read and examined this application and know the same to be true and correct. All provisions of law and ordinances governing this type of work will be complied with whether specified herein or not. The granting of permit does not presume to give authority to violate or cancel the provisions of any other state or local ordinances regulating construction or the performance of construction.

Plan check fee | Permit fee
Type of const. | Occupancy group &Div.
Size of bldg (Total sq ft) | No. of stories
Use zone | Max. Occ. load
Fire sprinklers reqd. Yes No
Special approvals
Zoning
Health Dept.
Fire Dept.
Soil report
Other (specify)

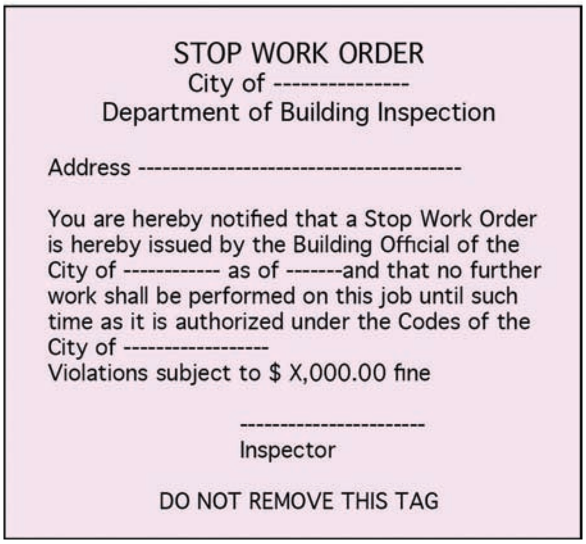
WHEN PROPERLY VALIDATED (IN THIS SPACE) THIS IS YOUR PERMIT

FIGURE 2.8 A typical building permit application.

PERIODIC AND SEQUENTIAL INSPECTION OF CONSTRUCTION, AND STOP WORK ORDER

Once construction begins, periodic and progressive inspections by the building official or the building official's representative—the building inspector—ensure that the construction meets with code requirements. The building is inspected at several stages during construction as per the sequence established by the building code. For example, below-ground mechanical, electrical and plumbing (MEP) lines (gas pipes; electrical and communication conduits; and water supply, sewage, and storm water pipes) are inspected prior to their being concealed by earth backfill or foundation concrete. Similarly, concrete reinforcement in structural elements is inspected before the placement of concrete, the wall framing and any insulation within framing is inspected prior to attaching gypsum board, and so on.

Inspections are conducted by the jurisdiction's inspectors, who are expert in their respective trades, such as civil and structural inspector, mechanical inspector, electrical inspector, plumbing inspector, and so on. Every inspection concludes with a report generated by the inspector to indicate whether or not construction is progressing in conformance with the code.



STOP WORK ORDER
City of ---------------
Department of Building Inspection

Address ---------------------------------------

You are hereby notified that a Stop Work Order is hereby issued by the Building Official of the City of ----------- as of -------and that no further work shall be performed on this job until such time as it is authorized under the Codes of the City of -----------------
Violations subject to $ X,000.00 fine

Inspector

DO NOT REMOVE THIS TAG

FIGURE 2.9 A typical stop work order notice.

In the case of a failed inspection, the owner is obliged to make immediate corrections and request reinspection until the construction is approved. If the corrections are not made or if, in the opinion of the inspector, a gross violation of the code has been committed, a *stop work order* by the city is issued, Figure 2.9. In some cases, the city may issue a partial stop work order that applies to a particular inspection, allowing the rest of the work to continue. In other cases, the stop work order may shut the entire work. Noncompliance with the stop work order results in administrative and/or legal action against the offender.

CERTIFICATE OF OCCUPANCY

Once the building is substantially complete (see Section 1.12), the owner may request a final inspection and apply for a *certificate of occupancy*. Permission to occupy the building is granted only after the city officials are satisfied that all work has been completed in accordance with the code.

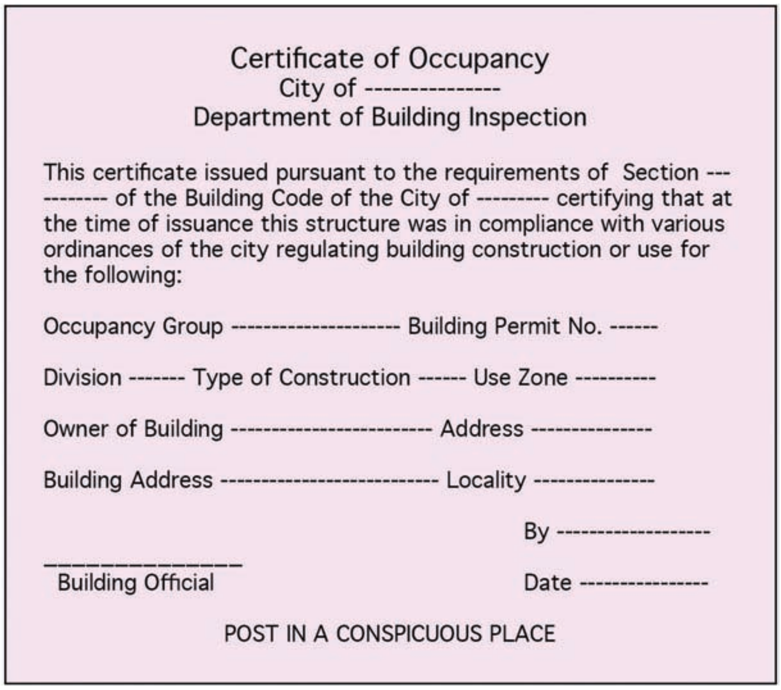
No building may be occupied, in whole or in part, until the certificate of occupancy has been granted. Among other details, a certificate of occupancy must specify the occupancy group and division of the building, the type of construction (Section 2.8), and any other special stipulation of the code, Figure 2.10.

BOARD OF APPEALS

A building code is a legal document, so it is a concise description of regulations as agreed to by the experts. Like most other laws, it does not contain any background material (except a brief commentary) that explains how decisions were made. A building code is, therefore, subject to interpretations, which may differ from jurisdiction to jurisdiction. In many cases, a clear-cut interpretation of a code provision may not even exist, because its original intent may have been either lost or not recorded.

In this situation, the owner (or the architect working as the owner's representative) may consult with the local building official for an interpretation. In the event of an unresolved difference between the interpretations of the owner and that of the building official, the building official's interpretation and decision are binding unless they are appealed.

Appeals against the building official's interpretation are referred to a *board of appeals*, which is usually a standing body of the city. The board's task is to hear appeals and adjudicate on the validity of the building official's decision. In some situations, the board may be requested by the building official to provide interpretation of an ambiguous code provision. This allows the entire board to assume responsibility for a particular interpretation, thereby reducing the building official's personal liability exposure.



Certificate of Occupancy
City of ---------------
Department of Building Inspection

This certificate issued pursuant to the requirements of Section ---------- of the Building Code of the City of -------- certifying that at the time of issuance this structure was in compliance with various ordinances of the city regulating building construction or use for the following:

Occupancy Group -------------------- Building Permit No. ------

Division ------- Type of Construction ------ Use Zone ---------

Owner of Building ------------------------ Address --------------

Building Address ------------------------- Locality --------------

By ------------------

____
Building Official

Date ---------------

POST IN A CONSPICUOUS PLACE

FIGURE 2.10 A typical certificate of occupancy.

The board of appeals is generally not authorized to waive any provision of the code, nor can it render judgment on the administrative provisions of the code. Its task is simply to interpret the technical aspects of the code, taking into account the code's objectives and intent. The board's decision is binding on the city, and in most cases, an appeal against the board's decision can be taken only to a court of law. The board consists of individuals who are qualified by training or experience in building codes and are not employees of the city. The building official usually serves as the ex-officio secretary of the board but does not have voting rights on the board.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. A building code regulates
- **a.** the design of the building.
- **b.** the construction of the building.
- **c.** the aesthetics of the building.
- **d.** all of the above.
- **e.** both (a) and (b).

2. In a building code, some life safety provisions are contained in fire safety provisions and the remaining ones in structural safety provisions.
- **a.** True
- **b.** False

3. The building code requirements for the dimensions of treads and risers of a staircase are
- **a.** fire safety issues.
- **b.** life safety issues.
- **c.** structural safety issues.
- **d.** health and welfare issues.
- **e.** property protection issues.

4. The building code requirements for the means of egress from a building are primarily
- **a.** fire safety issues.
- **b.** life safety issues.
- **c.** structural safety issues.
- **d.** health and welfare issues.
- **e.** property protection issues.

5. The enforcement of a building code is usually done at the level of the
- **a.** city in which the building is located.
- **b.** county in which the building is located.
- **c.** state in which the building is located.
- **d.** country in which the building is located.

6. The person in charge of enforcing the building code is generally called a
- **a.** code in-charge.
- **b.** building code representative.
- **c.** building code spokesperson.
- **d.** building official.
- **e.** none of the above.

7. Before commencing the construction of a building, the owner must apply to the city to obtain a
- **a.** commence work order.
- **b.** building license.
- **c.** construction permit.
- **d.** building permit.

8. To ensure that the construction of the building is being done in accordance with the building code, the city will arrange for its inspection
- **a.** only once during construction.
- **b.** two times during construction.
- **c.** three times during construction.
- **d.** several times during construction.

9. If during the construction of the building, the building inspector discovers a gross violation of the building code, he or she will generally
- **a.** invite the owner for a meeting.
- **b.** issue a warning to the owner.
- **c.** issue arrest warrant against the owner.
- **d.** issue a stop work order to the owner.
- **e.** take the owner to the appropriate court of law.

10. The board of appeals of the city does not have the authority to change building code provisions.
- **a.** True
- **b.** False

11. In the case of a dispute between the building official and the owner about the interpretation of a building code provision, the matter is first resolved by
- **a.** the owner's architect.
- **b.** an independent arbitrator mutually agreed to between the owner and the city.
- **c.** an ad hoc committee appointed by the city.
- **d.** the city attorney.
- **e.** none of the above.

2.3 PRESCRIPTIVE AND PERFORMANCE CODES

The older and traditional types of building codes are *prescriptive codes*. Such codes give clear prescriptions for construction systems, types of materials, and the devices to be used without permitting any alternatives. They are definitive in interpretation and are, therefore, easy to use and enforce. Their main drawback is that they cannot keep pace with the developments in building materials, technology, and safety concepts.

In a *performance code*, the performance criteria of a component are specified instead of the material or the construction system. The performance criteria are based on the function of the component. For example, a prescriptive code might require an 8-in.-thick brick wall as a party wall between two semidetached residential units, Figure 2.11. It might further specify the type of brick and the type of mortar to be used in joints. A performance code, on the other hand, states the required properties of the wall, such as the fire resistance, sound insulation, load-carrying capacity, durability characteristics, and so on.

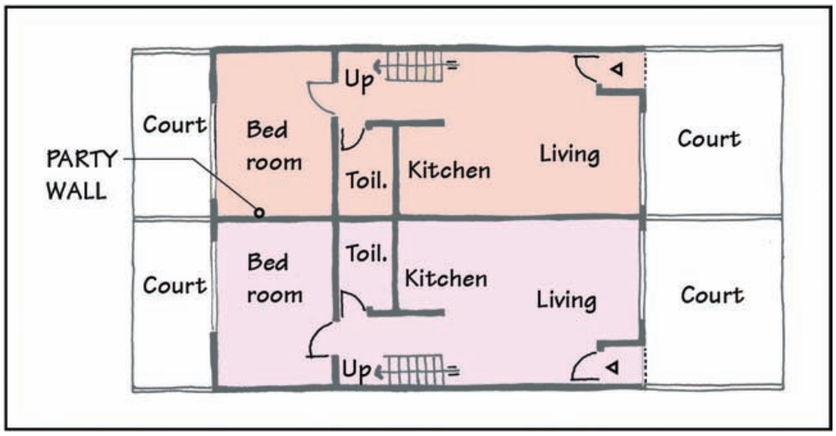
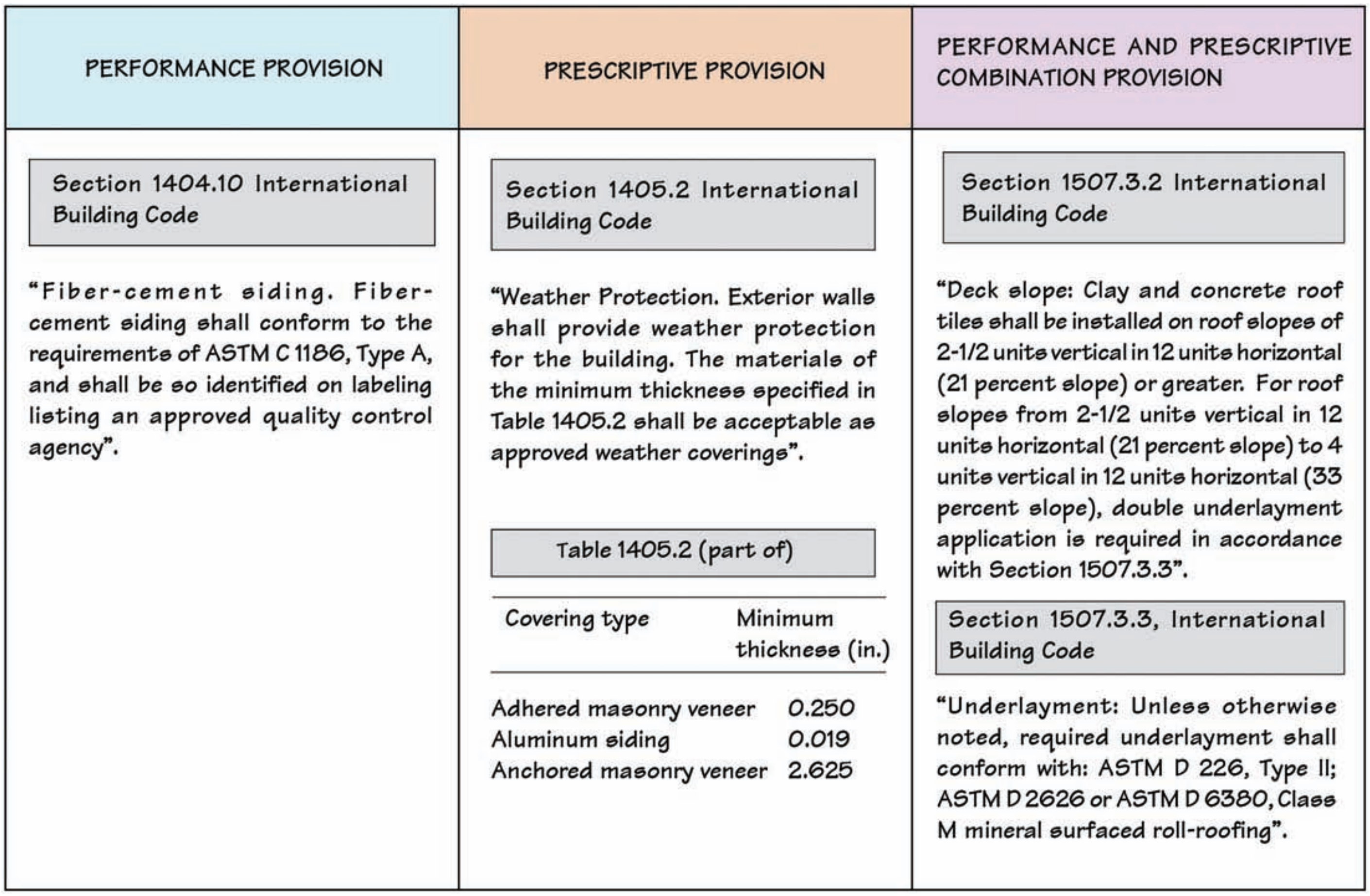


FIGURE 2.11 Two semidetached residential units with a party wall.

In a performance code, the choice of material and the thickness of the wall are left to the discretion of the designer. As long as the wall meets the stated performance requirements, it is acceptable regardless of its material or thickness. A performance code is, therefore, more flexible and provides greater freedom in the use of new building products or construction systems.

Although modern building codes have become increasingly performance oriented, they still include a considerable degree of prescriptiveness. Some code regulations are purely performance type, several others are purely prescriptive, and many are a combination of the two, Figure 2.12. As previously stated, early building codes were primarily prescriptive. In contemporary building codes, some prescriptive provisions exist because replacing them with performance provisions would introduce unnecessary complications, whereas others serve as an alternative to the performance provisions. Where alternative provisions (of a prescriptive nature) exist, the user of the code has the option to follow either the performance provisions or the prescriptive provisions.



PERFORMANCE PROVISION

Section 1404.10 International Building Code

"Fiber-cement siding. Fiber-cement siding shall conform to the requirements of ASTM C 1186, Type A, and shall be so identified on labeling listing an approved quality control agency".

PRESCRIPTIVE PROVISION

Section 1405.2 International Building Code

"Weather Protection. Exterior walls shall provide weather protection for the building. The materials of the minimum thickness specified in Table 1405.2 shall be acceptable as approved weather coverings".

Table 1405.2 (part of)

Covering type	Minimum thickness (in.)
Adhered masonry veneer	0.250
Aluminum siding	0.019
Anchored masonry veneer	2.625

PERFORMANCE AND PRESCRIPTIVE COMBINATION PROVISION

Section 1507.3.2 International Building Code

"Deck slope: Clay and concrete roof tiles shall be installed on roof slopes of 2-1/2 units vertical in 12 units horizontal (21 percent slope) or greater. For roof slopes from 2-1/2 units vertical in 12 units horizontal (21 percent slope) to 4 units vertical in 12 units horizontal (33 percent slope), double underlayment application is required in accordance with Section 1507.3.3".

Section 1507.3.3, International Building Code

"Underlayment: Unless otherwise noted, required underlayment shall conform with: ASTM D 226, Type II; ASTM D 2626 or ASTM D 6380, Class M mineral surfaced roll-roofing".

FIGURE 2.12 Examples of performance, prescriptive, and combination of performance and prescriptive provisions in a building code. The references to International Building Code (IBC) are for its 2015 edition.

For instance, conventional wood frame construction, used for low-rise single-family or multifamily dwellings, is in the hands of small builders, who may have neither the training nor the resources to effectively use the performance-type provisions. Therefore, building codes contain prescriptive (as well as performance) provisions that are applicable to conventional wood frame construction. A conventional wood frame building may comply with either the general performance-type provisions of the code or with the alternative prescriptive provisions.

2.4 MODEL CODES

There are two principal activities relating to building codes:

- Enforcement and interpretation of codes
- Formulation and updating of codes

As stated in Section 2.2, the enforcement of a code is mainly an administrative function handled by local jurisdictions. By contrast, the formulation and updating of building codes, which must be based on the latest knowledge in the realm of health safety and welfare (HSW), are beyond the resources of most local jurisdictions. These are complex activities that require the input of a large number of technical experts, such as architects, structural engineers, fire safety engineers, chemical engineers, builders, building officials, and building material manufacturers, to name just a few.

In most countries, therefore, building codes are developed by an independent agency, which not only reduces the cost burden on local governments but also avoids unnecessary duplication of work among them. Such a code, usually referred to as the *National Building Code* of the country, is then adopted by local governments. For example, the National Building Code of Canada is the only model building code in that country.

Although voluntary, the National Building Code of Canada has been adopted by various Canadian cities. The adoption is usually accompanied by local amendments to take into account the uniqueness of the jurisdiction. Thus, a model code is similar to a model house. A prospective home buyer may either seek to buy an exact replica of the model house or request that the builder make minor changes in the model house to suit the buyer's specific requirements.

Note that a model code is not a legal document unless it is adopted by a jurisdiction through appropriate legislation. Once adopted by a jurisdiction, it becomes the (legal) building code of that jurisdiction. In the United States, as in most other countries, the power of model code adoption rests with the states. In some states, this power has been delegated to the local jurisdictions—county or city.

HISTORY OF MODEL CODES IN THE UNITED STATES—THE LEGACY CODES

Because of the size and diversity of local conditions in the United States and because of the peculiar history of code development in this country, there were three model building codes (now called the *legacy codes*), developed by three independent model code–writing organizations, until the year 2000. Each model building code was an independent and complete document containing all necessary building code regulations. They were revised periodically, and a new edition of each code was published every three years.

The multiplicity of model codes had been a matter of great concern to the members of the design community because of the difficulties it created for them. The designers had to be familiar with all three model codes because the jurisdictions could adopt any one of them. It was quite common those days for two cities with a common boundary to adopt different model codes. Visualize the work of an architect developing a design for a national chain store. Uniformity of design might be essential to the marketing and distribution strategy of the chain. However, under the three-code setup, three separate versions of the same design were required to satisfy the requirements of three different codes, in addition to any local requirements.

THE INTERNATIONAL CODE COUNCIL (ICC)

In response to the criticism just described, the three model code organizations (International Conference of Building Officials, Southern Building Code Congress International, and Building Officials and Code Administrators International) merged and jointly founded the International Code Council (ICC) in 1994. The purpose of the merger and the establishment of ICC was to discontinue production of three separate model codes and to produce a common model code. In the year 2000, the first edition of ICC's building code, called the *International Building Code* (IBC), was published. Like the legacy codes, the IBC is updated on three-year cycle—year 2000, 2003, 2006 . . . 2015 . . . .

MODEL CODE ADOPTION

Although code enforcement is invariably done at the local level (city or municipality), the adoption of a model code in the United States may be done either at the city level or at the state level. The International Building Code has now been adopted at the state level by all 50 states of the United States plus Washington, D.C. Other model codes (described shortly), however, are adopted either at the local level or at the state level. For example, the International Residential Code has been adopted at the state level in some states and at the local level in other states.

Note again that a model code by itself has no legal authority unless it has been duly adopted by the jurisdiction. Generally, the adoption is made with a few minor changes to the model code to suit the jurisdiction's unique conditions dictated by its population size, socioeconomic conditions, and hence the resources available to regulate health, safety, and welfare issues related to buildings. Therefore because of these changes, there could, theoretically, be as many building codes as the number of jurisdictions in the country.

Note that the building activity is not regulated in every part of the country. Several rural areas in a state may be completely unregulated. Additionally, state and federal buildings are usually exempt from local or state building codes and follow their own codes.

TIME LAG BETWEEN THE PUBLICATION OF NEW MODEL CODE EDITION AND ITS ADOPTION

There is always a time lag between the publication of a model code edition and its adoption by a state or the local jurisdictions. As stated previously, a model code is not the legal code for a city unless the city's governing council has formally adopted it through an ordinance. This process takes time. In some cities, it may take several years. Thus, it is not uncommon to see a gap of several years (sometimes two or more three-year cycles) between the publication of a new edition of the model code and its adoption by a state or the local jurisdictions.

SPECIALTY CODES—PART OF THE ICC FAMILY OF CODES

A building is required to conform not only to the building code but also to a host of other specialty codes. However, the building code is the primary code, and most architects, structural engineers, and construction professionals need to be familiar only with the building code, leaving conformance with the specialty codes to be determined by the specialist consultants. The International Code Council (ICC) publishes all required specialty codes as part of the ICC family of codes (referred to as the *I-Codes*) some of which are shown in Figure 2.13 and described here:

- International Mechanical Code (IMC)—relating to heating, ventilating, and air-conditioning equipment, incinerators, and other mechanical equipment in buildings.
- International Plumbing Code (IPC)—relating to water supply, wastewater, and storm water disposal.
- International Electrical Code (IEC)—relating to the electrical systems in buildings.
- International Fire Code—to ensure the fire-safe maintenance of buildings (also called the *fire-prevention code*).
- International Energy Conservation Code (IECC)—to ensure the conservation of energy by buildings.

INTERNATIONAL RESIDENTIAL CODE (IRC)

Note that the International Residential Code (IRC), shown in Figure 2.13 is an alternative to the building code as well as the specialty codes. It is a comprehensive code that includes all provisions relating to the design and construction of a dwelling, including those related to mechanical, electrical, plumbing, energy conservation, and other systems. It is more prescriptive in nature than the International Building Code (IBC); hence easier to use. Thus, the specialty codes (IMC, IPC, etc.) are to be used only with the IBC.

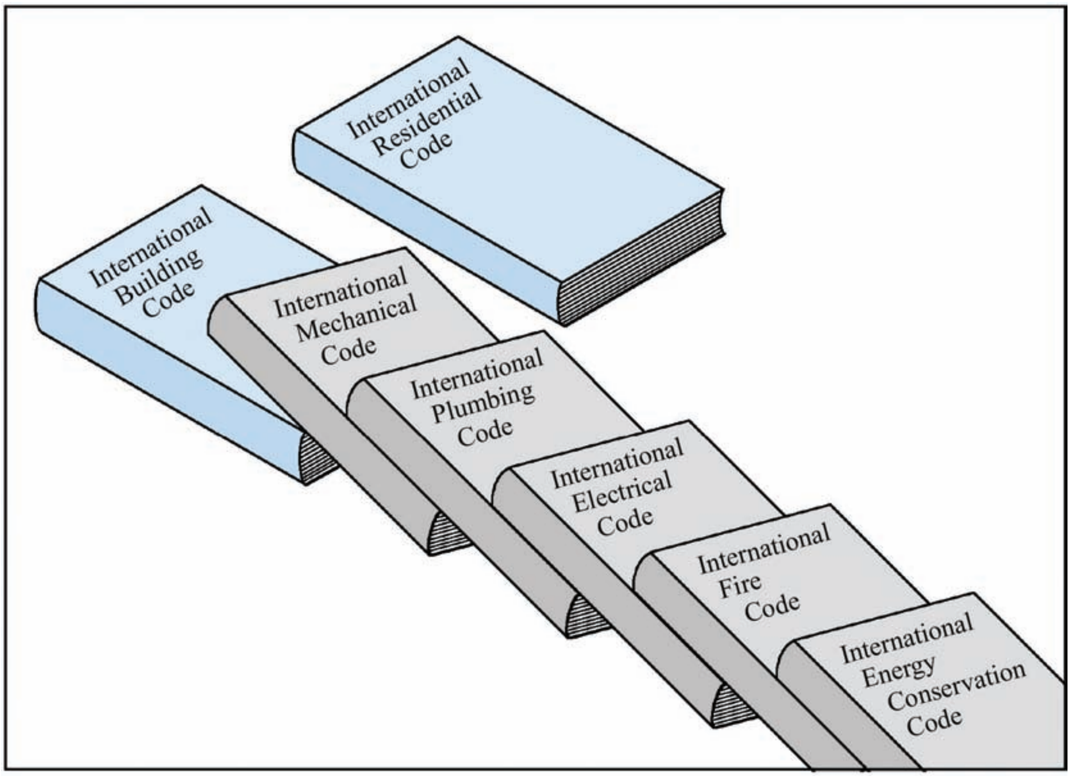

International Residential Code
International Building Code
International Mechanical Code
International Plumbing Code
International Electrical Code
International Fire Code
International Energy Conservation Code

FIGURE 2.13 Some of the model codes published by the International Code Council (ICC). The International Residential Code (IRC) is applicable to dwelling units only (see Figure 2.14), while the International Building Code (IBC) applies to all occupancies to which IRC does not apply. The IBC is complemented by specialty codes, such as the International Mechanical Code, International Plumbing Code, International Electrical Code, and so on. The IRC is a self-contained code and includes all specialty code provisions applicable to the dwelling units.

The IRC applies to one-family dwellings, two-family dwellings, and townhouses of not more than three stories, Figure 2.14. Thus, a one-family dwelling of four or more stories must be designed using the IBC. Note from Figure 2.14 that a townhouse is essentially a combination of one-family dwellings stacked in a row, where each dwelling has its own independent entry at the street level—like a one-family dwelling. A two-family dwelling is a combination of only two one-family dwellings in a semidetached combination.

INTERNATIONAL GREEN CONSTRUCTION CODE (IGCC)

The International Green Construction Code (IGCC) is the most recent addition to the ICC family of codes. Its first edition was published in 2012, and the second in 2015. Its purpose is to bring sustainable design and construction of built environment within the fold of code regulations, which began in the year 2000 with the publication of the first edition of the International Energy Conservation Code (IECC). IGCC goes several steps beyond IECC by including all other components of sustainability in built environment in addition to energy conservation, as detailed in Chapter 10.

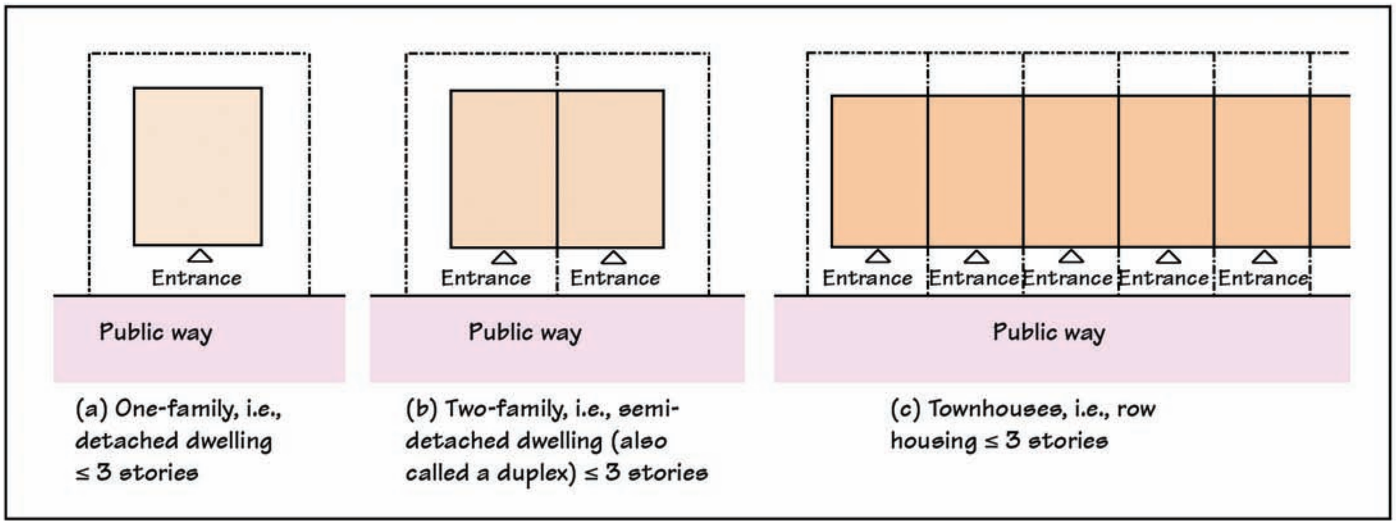

Entrance
Public way
(a) One-family, i.e., detached dwelling ≤ 3 stories
Entrance
Entrance
Public way
(b) Two-family, i.e., semi-detached dwelling (also called a duplex) ≤ 3 stories
Entrance
Entrance
Entrance
Entrance
Entrance
Public way
(c) Townhouses, i.e., row housing ≤ 3 stories

FIGURE 2.14 The International Residential Code (IRC) applies to one-family dwellings, two-family dwellings, and townhouses, each dwelling with its individual entrance from the public way and up to three stories tall.

IGCC is based on the sustained work accomplished by green building rating agencies such as the United States Green Building Council (USGBC) and the Green Building Initiative (GBI). The difference between the IGCC and the green rating agencies lies in the following three aspects.

i. Assessment of sustainability by green rating agencies is voluntary, while IGCC, once adopted by a jurisdiction (or a state), becomes mandatory for all buildings.
ii. The green rating agencies have several levels of sustainability ratings (see Chapter 10) and the building owner may choose the level desired, while IGCC provides only one, baseline level. The purpose of IGCC is, therefore, to ensure that all buildings of the jurisdiction have a certain minimum level of sustainability.
iii. IGCC does not have an independent existence but works as an overlay code with both the International Building Code and the International Residential Code, Figure 2.15. Additional details of IGCC are given in Chapter 10.

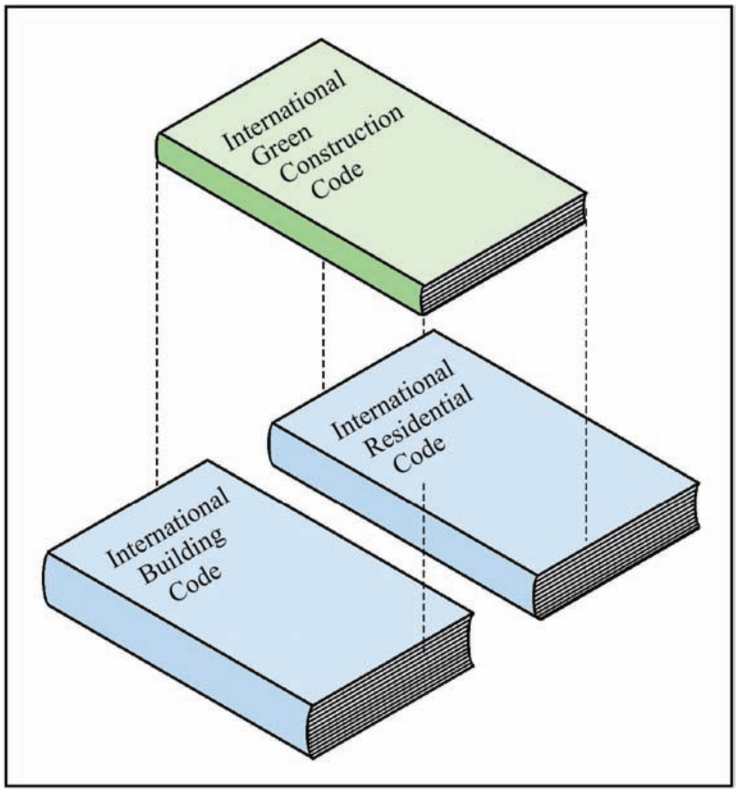

International Green Construction Code
International Residential Code
International Building Code

FIGURE 2.15 The International Green Construction Code (IGCC) is an overlay code that works with both the International Building Code as well as the International Residential Code.

2.5 CONTENTS OF A BUILDING CODE

A typical building code, such as the International Building Code, may be divided under the following nine parts:

i. **Code Administration:** Provisions deal with the administrative aspects of the code, such as the duties and functions of a building official, plans examination (examination of construction document set), board of appeals, issuance of a building permit, certificate of occupancy, construction inspections, and fees. The definitions of various terms used in the code are also contained in this part.
ii. **Building Planning:** Provisions deal with the classification of buildings according to their occupancy and type of construction. The occupancy of the building refers to the building's use. The type of construction refers to the fire resistance rating of the structural components of the building. These two factors—*occupancy classification* and the *type of construction*—are the two most important factors that determine the maximum allowable area of the building, maximum allowable height, and the maximum allowable number of stories above grade (ground).

   The third factor that influences the building's allowable area is its *frontage*. The frontage of a building refers to accessible open spaces around the building, such as the separation distance from adjacent buildings and from the lot (property) lines, Figure 2.16. The term "accessible" here means the accessibility of open space to a public way so that it can be used for occupant escape and for a fire truck to subdue the fire in the building. The greater the frontage, the lower the fire hazard the building presents to its occupants and the neighboring buildings and hence the greater the building's allowable area. For the same reason, if the building is provided with *automatic sprinklers*, its allowable area and height is greater.
iii. **Fire Protection:** Provisions deal with fire-resistive materials and construction, fire-resistive interior finishes, and fire protection systems. Fire protection systems include those that detect and suppress fires.
iv. **Occupant Needs:** Provisions deal with the means of egress, accessibility, and interior environment, including lighting, ventilation, sanitation, and sound control.
v. **Building Envelope:** Provisions deal with the performance of the exterior envelope of the building—exterior walls, cladding, windows, roof, and so forth.
vi. **Structural Systems and Materials:** Provisions deal with loads on buildings, structural tests and inspections, and foundations. This is the most extensive part of the code and includes a separate chapter for each structural material—concrete, masonry, steel, and wood.
vii. **Nonstructural Materials:** Provisions deal with the use of nonstructural materials, such as aluminum, glass, gypsum board, and plastics.

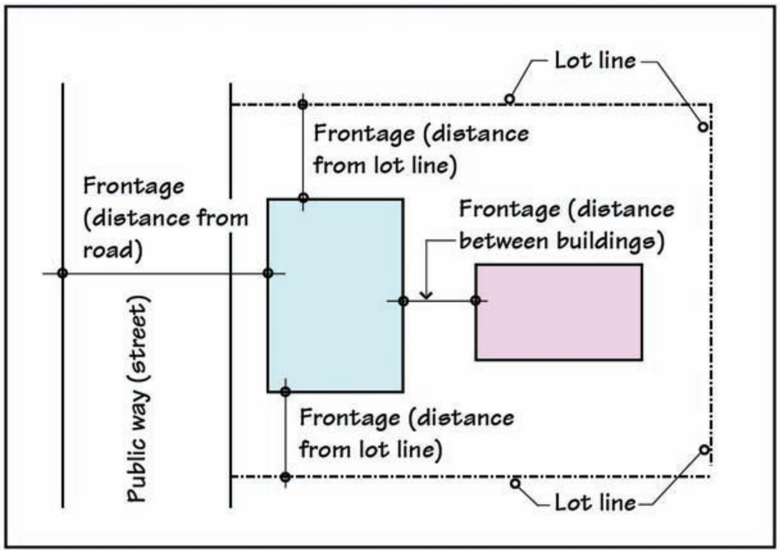

Lot line
Frontage (distance from lot line)
Frontage (distance from road)
Frontage (distance between buildings)
Public way (street)
Frontage (distance from lot line)
Lot line

FIGURE 2.16 The separation of a building from the lot lines and the adjoining buildings, located within the same lot, provides open spaces around the building. If these spaces are accessible to a public way (or street), they can be used for fire fighting measures. Building codes recognize accessible open spaces (referred to as *frontage*) in determining the allowable area of the building (see Principles in Practice at the end of this chapter). Note that the separation distance of the building from a street is measured from the far end of the street.

viii. **Building Services:** Provisions deal with electrical, mechanical, and plumbing aspects relevant to architectural design (excluding technical aspects of these systems, which are covered in specialty codes).

ix. **Miscellaneous Provisions:** Deal with miscellaneous concerns, such as construction in the public right of way, site work, demolition, and existing structures.

2.6 APPLICATION OF A BUILDING CODE

Experienced design and construction professionals realize that a building code is a large, complex document. Therefore, they consider the essential features of the code early in the design process and gradually introduce its details as the design process progresses.

Because of the code's complexity, only a brief overview of the application of building code to a proposed building is presented here. The most important features of this process, subdivided into eight steps, are illustrated in Figure 2.17.

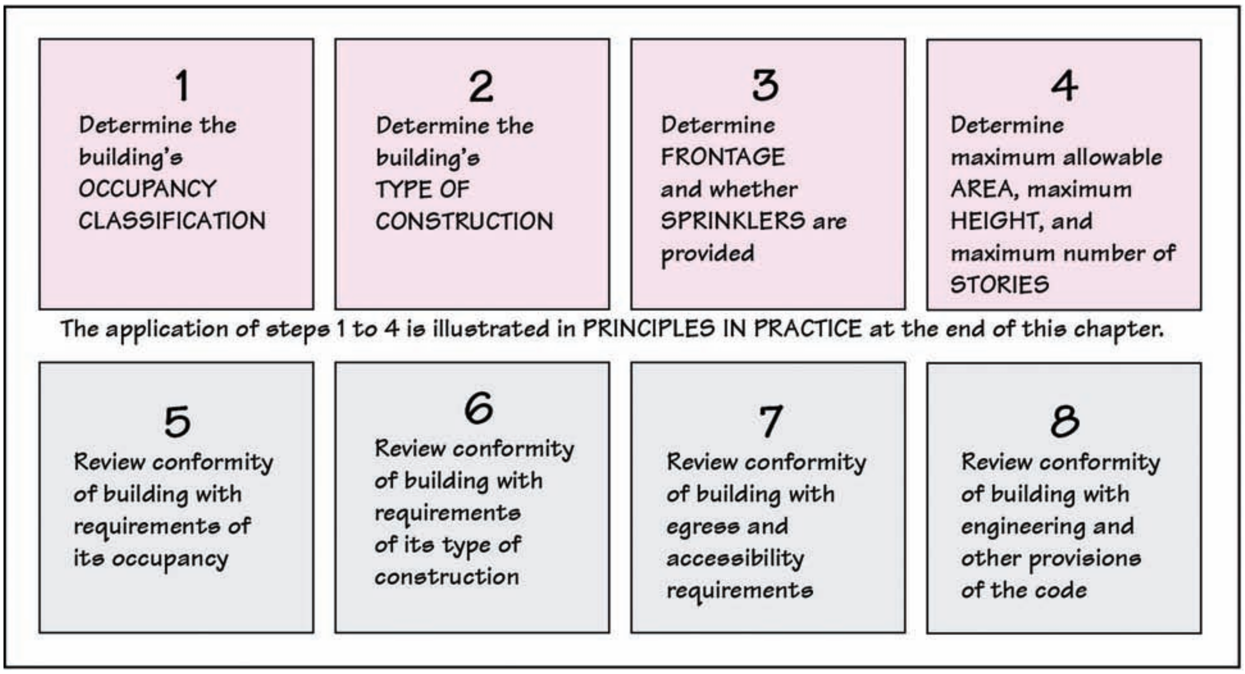

1
Determine the building's OCCUPANCY CLASSIFICATION
2
Determine the building's TYPE OF CONSTRUCTION
3
Determine FRONTAGE and whether SPRINKLERS are provided
4
Determine maximum allowable AREA, maximum HEIGHT, and maximum number of STORIES
The application of steps 1 to 4 is illustrated in PRINCIPLES IN PRACTICE at the end of this chapter.
5
Review conformity of building with requirements of its occupancy
6
Review conformity of building with requirements of its type of construction
7
Review conformity of building with egress and accessibility requirements
8
Review conformity of building with engineering and other provisions of the code

FIGURE 2.17 Steps involved in the application of a building code to a proposed building.

Step 1: Determine the occupancy classification of the building.

Step 2: Determine the building's type of construction.

Step 3: Determine the building's frontage and whether or not automatic sprinklers are provided.

Step 4: Determine the maximum allowable area, maximum allowable height, and the maximum number of stories of the building. This is related to the degree of hazard present in the building. The fundamental premise of a building code is to have almost the same degree of life-safety risk in all buildings, referred to as *equivalent risk theory*. Thus, if the hazard present in the building is small, the allowable area and height of the building is large. Conversely, if the hazard present is large, the allowable area and height of the building is small.

The hazard posed by a building is a function of its occupancy, type of construction, frontage, automatic sprinklers, area, and height. The more fire-resistive the construction type and (or) the greater the frontage, the lower the hazard. The provision of automatic sprinklers also reduces the hazard. The larger and (or) taller the building, the greater the hazard it poses.

Steps 5–8: Review the conformity of the building to the detailed provisions of its particular occupancy (Step 5), type of construction (Step 6), egress and accessibility requirements (Step 7), and structural engineering requirements and specialty codes (Step 8).

NOTE

Factors That Determine the Code-Allowed Area, Height, and Stories of Building

The following factors determine the allowable area, height, and the number of stories of a building (see Principles in Practice at the end of this chapter).

- Occupancy classification of building
- Type of construction of building
- Frontage (open spaces) around building
- Building is sprinklered or nonsprinklered

2.7 OCCUPANCY CLASSIFICATION OF A BUILDING

Of the various factors that pose hazards in a building (as mentioned previously), its occupancy is most critical. Occupancy-related hazard in a building depends primarily on the following aspects.

Concentration of Occupants: Buildings that accommodate a large number of people, such as stadiums, assembly halls, auditoriums, and houses of worship, present a greater hazard than buildings with a smaller concentration of occupants, such as individual dwellings and apartment buildings.

Fuel Content: Buildings that contain flammable materials, such as automobile repair garages, paint and chemical stores, and woodworking mills, are more hazardous because they contain more combustibles than other buildings.

Mobility of Occupants: Buildings such as nursing homes, hospitals, day care centers, and prisons have occupants whose mobility is severely limited. Such buildings present a great deal of hazard because their occupants cannot exit in the event of a fire or some other emergency.

Familiarity of Occupants with the Building: The greater the occupants' familiarity with the building, the lower the hazard. This conclusion is based on the premise that in the event of a fire or some other emergency, the occupants will be able to exit the building easily if they are familiar with it. For example, a hotel building is more hazardous than an apartment dwelling, and an apartment building is more hazardous than an individual dwelling.

OCCUPANCY GROUPS AND THEIR SUBDIVISIONS

The International Building Code classifies buildings into 10 occupancy groups. Each occupancy group is given a letter designation, such as A, B, . . ., U and is further classified into subgroups, called *divisions*. For example, the Assembly occupancy is divided into five divisions, which are designated as A-1, A-2, A-3, A-4, and A-5, Table 2.1.

Note that the occupancy of a building is represented by its occupancy group and its division, if the group is divided into more than one divisions. Therefore, there is no occupancy called Occupancy A. It can be any one of A-1, A-2, and so on. However, a building can be Occupancy B because group B does not have any divisions.

Generally, the hazard present in occupancies decreases with increasing division number. Thus, Occupancy A-2 is generally less hazardous than Occupancy A-1, A-3 is less hazardous than A-2, and so on.

MIXED OCCUPANCY AND OCCUPANCY SEPARATION

A building may consist of one occupancy or more than one occupancy. The latter is referred to as a *mixed-occupancy building*. Mixed-occupancy buildings are fairly common. For instance, a hotel may consist of bedrooms and a few conference rooms. Hotel bedrooms are

TABLE 2.1 OCCUPANCY CLASSIFICATIONS OF BUILDINGS

Occupancy Group	Occupancy Group Divisions Generally decreasing hazard →				
A **Assembly**	**A-1** Movie theater, TV and radio stations, concert hall, etc.	**A-2** Banquet hall, restaurant, night clubs, etc.	**A-3** House of worship, gymnasium, library, lecture hall, etc.	**A-4** Skating rink, swimming pool, tennis court, etc.	**A-5** Stadium, grandstand, amusement park, etc.
B **Business**	Bank, professional offices (architects, attorneys, doctors, etc.), beauty shop, fire and police stations, post office, educational institution beyond grade 12, etc.		**Small Assembly Spaces:** A room or space used as an assembly space for ≤ 49 persons or ≤ 750 sq ft in area and accessory to (extension of) another occupancy shall be classified as Group B occupancy or as part of that occupancy. For example, a lunch room for ≤ 49 persons in F-2 occupancy can be treated as F-2 occupancy, precluding the need for occupancy separations. **Group E Occupancy:** All assembly spaces in Group E occupancy, such as auditoriums and gymnasiums, are not considered as separate occupancies.		
E **Educational**	Educational buildings upto grade 12 with 6 or more students at any one time and day care centers for at least 5 children 2-1/2 years or older.				
F **Factory**	**F-1** Automobile, bicycles, clothing, furniture, etc.	**F-2** Beverages, brick and masonry, glass, gypsum, etc.			
H **High-Hazard**	**H-1** Structures with explosives, unstable chemicals, etc.	**H-2** Structures with combustible dust, flammable gas, etc.	**H-3** Structures with aerosols, flammable solids, etc.	**H-4** Structures with toxic materials, etc.	**H-5** Structures with semiconductor fabrication, etc.
I **Institutional**	**I-1** Convalescent home, assisted living facility, etc.	**I-2** Hospital, nursing home, 24-hour medical care, etc.	**I-3** Prison, detention center, correction center, etc.	**I-4** Adult care and day care facilities for < 24 hours, etc.	
M **Mercantile**	Department store, drugstore, market, motor vehicle service center, etc.				
R **Residential**	**R-1** Transient living—hotel, motel, etc.	**R-2** Permanent living—apartments, dormitories, etc.	**R-3** One- or two-family dwellings, lodging houses, etc.	**R-4** Assisted living facility for 5 to 16 people, etc.	
S **Storage**	**S-1** Aircraft hangar, furniture, clothing, grain, etc.	**S-2** Cement, glass, parking garages open or enclosed, etc.			
U **Utility**	Agricultural building, carport, greenhouse, livestock shelter, etc.				

Source: 2015 International Building Code, Chapter 3.

Occupancy R-1, whereas conference rooms are classified as A-3. Similarly, an office block may consist of individual offices, a day care center, a gymnasium, and a few retail shops. The individual offices are Occupancy B, a day care center is Occupancy E, a gymnasium is Occupancy A-3, and retail shops are Occupancy M.

Because of the variable degree of hazard present in a mixed occupancy, the building code requires that each occupancy be separated from the other occupancy by an occupancy separation of a specified minimum fire resistance. For example, the code stipulates that in a hotel building consisting of R-1 and A-3 Occupancies, the separation between these two occupancies must have a minimum fire resistance of 2 h, Figure 2.18. The occupancy separation (which is a fire-rated element) may be a wall, floor, or both. The objective is to separate the two occupancies vertically as well as horizontally.

SEPARATED AND NONSEPARATED MIXED OCCUPANCIES

If the required occupancy separation is not provided, the building is called a *nonseparated mixed-occupancy building*, and the entire building is treated as belonging to the more hazardous occupancy, adversely affecting the allowable area and height of the building. In the example of Figure 2.18, if the building is not provided with separations as shown, the entire building will be treated as Occupancy A-3, because this is more hazardous than Occupancy R-1. The allowable area and height of the building will be as permitted for Occupancy A-3.

If the required occupancy separation is provided (called a *separated mixed-occupancy building*), the building will be considered one building with two distinct occupancies, and each occupancy can have its own allowable area and height. Additional details of the allowable area and height of a building (including a mixed-occupancy building) are given in Principles in Practice at the end of this chapter.

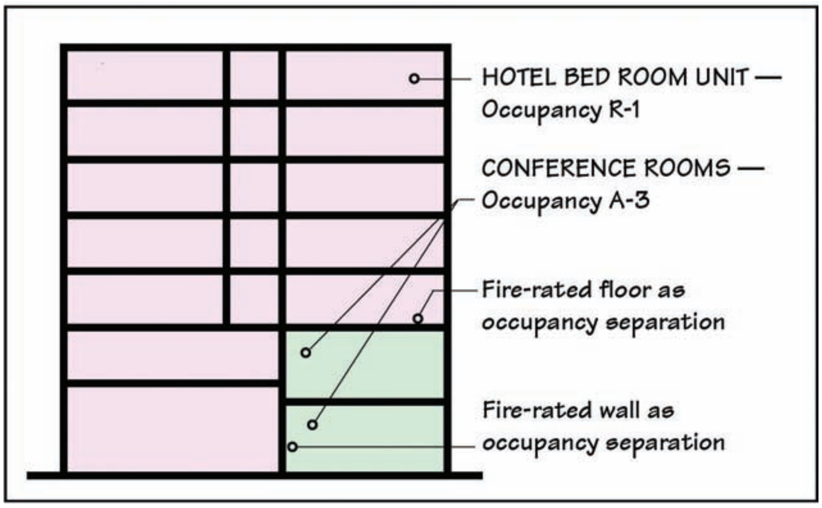

HOTEL BED ROOM UNIT — Occupancy R-1
CONFERENCE ROOMS — Occupancy A-3
Fire-rated floor as occupancy separation
Fire-rated wall as occupancy separation

FIGURE 2.18 The separation between two different occupancies in a building is called an *occupancy separation*. In this illustration, the two different occupancies shown are hotel bedrooms (Occupancy R-1) and conference rooms (Occupancy A-3). An occupancy separation may be a wall, a floor, or both, each of which must have the minimum fire resistance rating specified by the code. If occupancy separations are not provided (i.e., if nonseparated occupancies are provided), the entire building will be treated as belonging to the more hazardous occupancy.

ACCESSORY-USE SPACES NOT CONSIDERED AS SEPARATE OCCUPANCIES

Some buildings have one dominant occupancy and one or more minor occupancies that are subsidiary to the main occupancy. If the aggregate floor area of the minor occupancies is less than 10% of the total area of the building on any floor, the minor occupancies may be treated as *accessory-use spaces*. An occupancy with accessory-use space(s) may be considered a single (dominant) occupancy, requiring no separation between the main occupancy and the accessory-use space(s).

For example, consider a high-rise apartment building with apartment management office (Occupancy B), beauty salon (Occupancy B), and general store for minor food and miscellaneous items (Occupancy M) at the ground floor, Figure 2.19. The dominant occupancy of the building is R-2 (see Table 2.1). Because the office, beauty salon, and general store are subsidiary to the apartment building, and because their aggregate area is less than 10% of the total area of the floor where these spaces are located (i.e., the ground floor), they qualify as accessory-use spaces. Therefore, the entire building will be classified as Occupancy R-2.

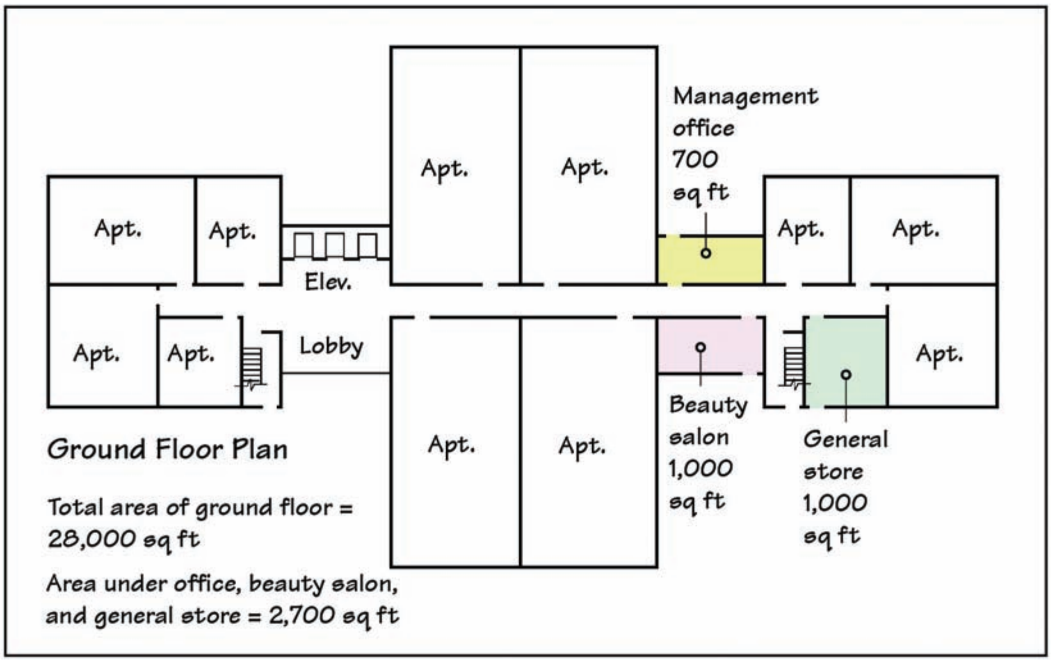
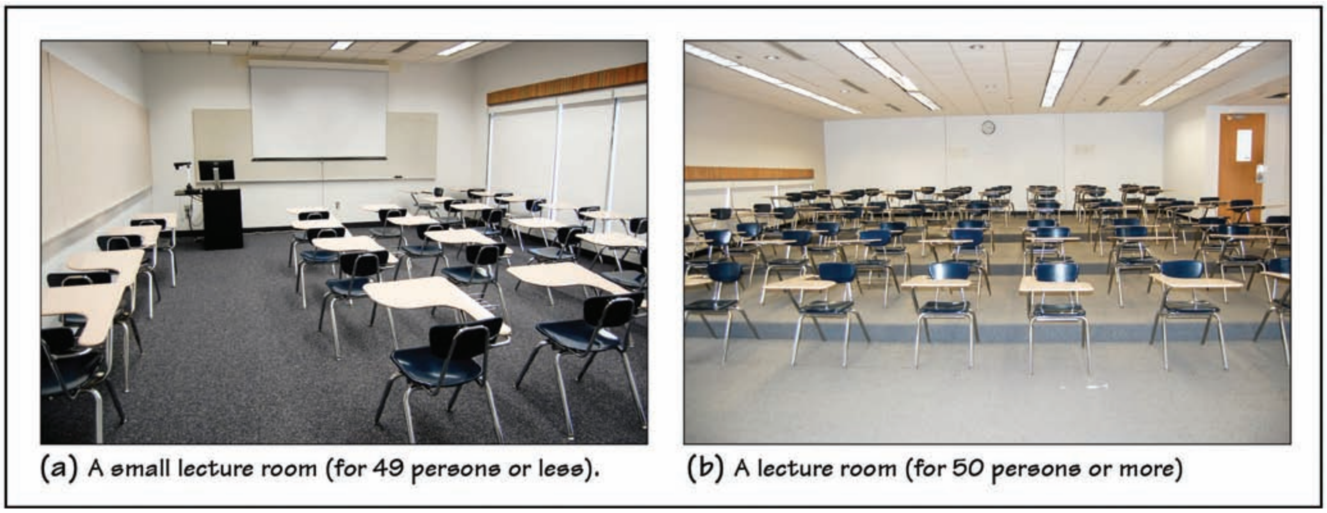

Apt.
Apt.
Apt.
Apt.
Management office 700 sq ft
Apt.
Apt.
Elev.
Apt.
Apt.
Lobby
Apt.
Ground Floor Plan
Total area of ground floor = 28,000 sq ft
Area under office, beauty salon, and general store = 2,700 sq ft
Apt.
Apt.
Beauty salon 1,000 sq ft
General store 1,000 sq ft

FIGURE 2.19 In this high-rise apartment building (Occupancy R-2), apartment management office (Occupancy B), beauty salon (Occupancy B), and general store for minor food items (Occupancy M) are legitimate accessory-use spaces, and because their total area (2,700 sq ft) is less than 10% of the total area of the building (28,000 sq ft) at the floor where the accessory spaces are located, the entire building qualifies as Occupancy R-2.



(a) A small lecture room (for 49 persons or less).

(b) A lecture room (for 50 persons or more)

FIGURE 2.20 A lecture room to accommodate 49 persons or less in a college building is assigned to Occupancy B. If the lecture room in the same building accommodates 50 persons or more, it is assigned to Occupancy A-3.

INCIDENTAL-USE SPACE

Some minor occupancies may be more hazardous than the dominant occupancy. Such occupancies are not treated as accessory-use spaces but as *incidental-use spaces*. For example, a covered parking garage in a high-rise office building is an incidental-use space. Incidental-use spaces require a fire-rated separation from the main occupancy. The IBC lists the spaces that should be treated as incidental-use spaces and gives the corresponding fire-rating requirement of the separation.

LOW HAZARD IN SMALL ASSEMBLY SPACES

Safety concerns are significant in assembly spaces because of their large congregations. However, several buildings contain small assembly spaces, such as lecture rooms, meeting rooms, restaurants, and so on, where such concerns are relatively low. In recognition of this fact, the code allows that the assembly spaces for the use of 49 persons or less (or ≤ 750 sq ft in area) may be assigned to Occupancy B, or to the occupancy in which the assembly space is located provided it is accessory to that occupancy. The 10% limitation, applicable to a normal accessory-use space, does not apply. If the assembly space accommodates 50 persons or more, then it is assigned to appropriate assembly occupancy—Occupancy A-1, or A-2, or A-3, etc.

For example, a classroom for fewer than 50 students in a college building is classified as Occupancy B, while a classroom or auditorium for 50 students or more is classified as Occupancy A-3, Figure 2.20. Assembly spaces in Occupancy E (schools up to grade 12) are not considered as separate occupancies, but as Occupancy E.

TABLE 2.2 TYPE OF CONSTRUCTION CLASSIFICATION OF BUILDINGS

Type of Construction		Decreasing fire resistance	
Decreasing fire resistance	**Type I**	Type I(A)	Type I(B)
	Type II	Type II(A)	Type II(B)
	Type III	Type III(A)	Type III(B)
	Type IV	No subclassification	
	Type V	Type V(A)	Type V(B)

Source: 2015 International Building Code, Chapter 6.

2.8 TYPE OF CONSTRUCTION CLASSIFICATION OF A BUILDING

The building's type of construction also creates its own hazard. The more fire resistive the construction, the smaller the hazard. The International Building Code classifies construction into five basic types—I, II, III, IV, and V. This classification is based on the degree of fire resistance of various structural components of the building, such as floors, roof, columns, beams, exterior walls, and interior partitions.

Type I is the most fire-resistive construction, and Type V is the least fire-resistive. Each of these types is further subdivided into two subtypes, except Type IV (which has no subtype), Table 2.2. A detailed description of the types of construction is given in Chapter 7.

Each question has only one correct answer. Select the choice that best answers the question.

12. A prescriptive building code provision is easier to enforce than a performance provision.
a. True **b.** False

13. Performance-type building code provisions inhibit the use of innovative building materials and construction systems compared with prescriptive type provisions.
a. True **b.** False

14. Writing and periodically updating the building code in the United States is generally done by
a. the individual city.
b. the individual state.
c. the federal government.
d. a specialized independent agency.

15. The International Building Code is published by the
a. U.S. government.
b. International Conference of Building Officials.
c. Building Officials and Code Administrators International.
d. North American Council of Governments.
e. None of the above.

16. The International Building Code is generally updated every
a. 2 years. **b.** 3 years.
c. 4 years. **d.** 5 years.
e. 10 years.

17. The adoption of a model building code in the United States is done at the level of
a. the entire country. **b.** each state.
c. each city. **d.** either (a) or (b).
e. either (b) or (c).

18. The first step in applying the building code to a project is to
a. determine if the building is provided with an automatic sprinkler system.
b. determine the width of open spaces around the building.
c. determine the occupancy classification of the building.
d. determine the number of exits from the building at the ground floor.

19. The total number of occupancies (excluding the divisions) as specified in the International Building Code is
a. 6. **b.** 8.
c. 10. **d.** 12.
e. none of the above.

20. Which of the following is not a recognized building code occupancy?
a. Assembly **b.** Educational
c. Business **d.** Office
e. Institutional

21. A hotel building is a
a. business occupancy. **b.** mixed occupancy.
c. hotel occupancy. **d.** hospitality occupancy.
e. none of the above.

22. The International Building Code divides the types of construction into
a. Types U, V, X, and Y. **b.** Types 1, 2, 3, 4, and 5.
c. Types I, II, III, IV, and V. **d.** Types I, II, III, IV, V, and VI.

23. The most fire resistive type of construction is
a. Type I. **b.** Type 5(A).
c. Type II. **d.** Type V(A).
e. Type I(A).

24. The International Green Construction Code (IGCC) is published by the
a. United States Green Building Council (USGBC).
b. Green Building Initiative (GBI).
c. Green Globes.
d. ASTM International.
e. International Code Council.

2.9 CONSTRUCTION STANDARDS

Standards are the foundations of modern building codes. They contain technical information that addresses: (a) the properties of a building product or a component, (b) test methods to determine the properties of materials, and (c) the method of installation or construction.

The word *standard* is used here as a qualifier for words such as the *properties, test methods*, or the *method of installation*. Thus, a standard, in fact, refers to one of the following:

Standard Specification: This deals with the quality of materials, products, and components.

Standard Test Method: This determines the particular performance of a product or system through a test including methods of sampling and quality control.

Standard Method of Practice—Construction Practice, Installation Practice, or Maintenance Practice: This includes specific fabrication, installation, and erection methods of a component, including its maintenance.

A standard should not be confused with a building code provision. Although a code specifies the design criteria or the required properties of a component, the standard specifies the procedures and equipment required to verify the criteria or measure the properties. For instance, a building code will give the required fire resistance (e.g., 2 h) for a wall, roof, floor, and so on. The construction standard prescribes the test procedure and equipment required to measure the fire resistance of that element.

A fully prescriptive code does not require any standards because it does not refer to any performance criterion or property. By contrast, a performance-type code must rely heavily on the use of standards. As the trend toward performance-type code provisions has grown, the use of standards in building codes has increased accordingly.

2.10 STANDARD WRITING ORGANIZATIONS

The development of standards is beyond the scope of local jurisdictions or a model code organization, because of the large number of standards that must be referenced by a model code. Therefore, the tasks of formulating and updating the standards are performed by organizations that have the necessary facilities and expertise for obtaining and evaluating the performance data. These organizations may be divided into four types: trade associations, professional societies, governmental organizations, and organizations whose primary purpose is to create, maintain, and publish standards.

TRADE ASSOCIATIONS

A trade association is an association of manufacturing companies making the same product. For example, the American Wood Preservers' Association (AWPA) is an organization whose membership comprises industries that treat lumber, plywood, and other wood products with preservatives and fire-retardant chemicals. Some other important trade organizations involved in writing standards are the National Roofing Contractors' Association (NRCA), Brick Industry Association (BIA), National Concrete Masonry Association (NCMA), and Tile Council of North America (TCNA).

The function of a trade association is to coordinate the tasks of member companies and to protect their interests. It deals with all matters that affect the specific industry, such as collecting statistics, dealing with tariffs and trade regulations, and disseminating information about the product to design and construction professionals, particularly emphasizing their benefits over those of any competing or alternative product.

In order to ensure quality and competitiveness, most trade associations publish standards for the products they serve, to which all member companies must conform. Several trade associations also have certification programs to grade and stamp the product. AWPA is such an organization, and an AWPA grade stamp on wood and wood products is regarded as a mark of quality and standardization.

PROFESSIONAL SOCIETIES

The professional societies, such as ASCE (American Society of Civil Engineers), ASHRAE (formerly known as the American Society of Heating, Refrigeration and Air Conditioning Engineers), and ICC (International Code Council) are some other sources of standards. These organizations develop standard specifications and testing procedures as professional obligations. For example, the ASCE's publication *Minimum Design Loads for Buildings and Other Structures*, ASCE 7 Standard, is heavily referenced by the building codes.

GOVERNMENTAL ORGANIZATIONS

Examples of such organizations include the U.S. Department of Housing and Urban Development (HUD), Federal Emergency Management Association (FEMA), U.S. Department of Commerce (DOC), and Consumer Product Safety Commission (CPSC).

ORGANIZATIONS WITH STANDARDS PRODUCTION AS THEIR PRIMARY PURPOSE

By far the largest and most frequently referenced standards-producing organizations are those whose main function is to produce standards. In countries other than the United States, this task is normally handled by a single umbrella organization at the national level. In Britain there is the British Standards Institution (BSI), in Australia the Standards Association of Australia (SAA), and in Germany the Deutsches Institute fur Normung (DIN).

In the United States, the picture is somewhat less clear because of the large number of organizations involved in the development of standards at the national level. Three primary standards-producing organizations in the United States are:

- American National Standards Institute (ANSI)
- ASTM International
- Underwriters Laboratories (UL)

American National Standards Institute (ANSI) is a body similar to, but not identical to, national standards organizations in other countries, such as the BSI, DIN, and SAA. Unlike these organizations, however, the ANSI generally does not develop its own standards. It functions primarily as the approving body and a clearinghouse at the national level for voluntary standards developed by other organizations in the United States. Thus, it provides an official and a nationally recognized status to standards developed by private organizations.

ANSI ensures that the standards it approves have been developed in an open and fair manner after due consultations among various interest groups, such as producers, users, professional experts, and the general public. If no standard exists for a product, ANSI will bring together and coordinate the expertise needed to develop the required standards.

Founded in 1918, the ANSI is a nongovernmental and privately financed body, obtaining its funding primarily from membership dues and the sale of its publications. However, it represents the United States in the International Standards Organization (ISO).

ASTM International was founded in 1898. It is a privately funded, nonprofit organization that was, established for the development of standards on the characteristics and performance of materials, products, systems, and services and the promotion of related knowledge. It is by far the largest single source of standards in the world.

The society was established as the American Section of the International Society for Testing Materials and incorporated in 1902 as the American Society for Testing Materials. In 1961, its name was changed to the *American Society for Testing and Materials* to emphasize its interest in the materials as well as their testing. In 2001, its name was changed again to its present name, *ASTM International*, to reflect the global use of its standards and, consequently, the participation of worldwide experts in the writing of its standards.

ASTM standards are “voluntary consensus standards”. The word *voluntary* implies that the standard is not mandatory, unless so required by a code or regulation that references it. In other words, the existence of an ASTM standard for a particular product (or procedure) does not mean that it cannot be produced (or used) if it does not conform to the standard. The word *consensus* implies that the standard is arrived at by a consensus of various members of the committee or subcommittee that produced it.

Underwriters Laboratories (UL) was established in 1894 by insurance companies, which were paying excessive claims caused by fires generated by the failures of new electrical and mechanical devices in buildings. Today, UL is a self-supporting, not-for-profit organization that finances itself through the testing of various building and engineering products and the sale of its publications.

Currently, UL maintains four testing laboratories in the United States, with its corporate headquarters in Northbrook, Illinois. It also certifies and labels products. The UL mark on a product is a certificate of its having successfully undergone some of the world’s most rigorous tests for safety evaluation. In other words, the UL mark indicates that the product is safe and free from any foreseeable risk of hazard.

UL is an independent organization, which means that it has no monetary interest in the product or its success in the marketplace. If a product passes UL’s required safety testing and the manufacturer wants it to carry the UL mark, the UL’s field representative visits the manufacturing facilities unannounced several times during a year to ensure continued compliance of the product with the required safety standards. Certified products are listed in the UL directories, which are published annually.

In the building industry, UL is known mainly for testing the fire-resistance rating of building components. The tests must obviously be conducted according to recognized standards. Currently, UL has approximately 500 standards, most of which are approved as ANSI standards.

2.11 OTHER MAJOR REGULATORY CONSTRAINTS

In addition to building codes and specialty codes, building design and construction must also conform to several other regulations and constraints. The two most important such constraints are:

- Zoning ordinances
- Accessibility standards—Americans with Disabilities Act (ADA)

In addition to the zoning ordinance and ADA regulations, building design and construction may require conformance with several other requirements of the state or federal government provided as design guides. These guides are generally specific to a building type. For example, a multifamily housing design must conform to the requirements laid down by the U.S. Department of Housing and Urban Development (HUD) in response to the *Fair Housing Act*.

Similar guidelines apply to hospitals, schools, food-processing plants, and so on. Industrial and commercial buildings generally need to conform to requirements laid down by the insurance industry for coverage against property losses. Most insurance industry requirements exceed the corresponding requirements of the building code.

2.12 ZONING ORDINANCE

A *zoning ordinance* (also called a *zoning code*) of a city or county is a document containing urban planning laws. It regulates the use of land under the jurisdiction of the city according to a comprehensive master plan to promote health, safety, and welfare (HSW) of its citizens by formulating orderly and wholesome urban development. Because a wholesome development attracts new business from other areas of the country, a well-conceived and resilient zoning ordinance impacts the city's economy favorably by increasing property prices, and hence, the tax revenues.

ZONING DISTRICTS

An essential feature of a zoning ordinance is to segregate the land of a city into different land-use groups so that incompatible uses are separated by open spaces or by development that is intermediate between the two groups. For example, a residential development may be separated from a commercial development (containing skating rinks, nightclubs, liquor shops, etc.) by a low-intensity commercial development (containing professional offices, beauty shops, bookstores, drug stores, restaurants, etc.).

The parcels of land on which similar activities are permitted are called *zoning district groups*, or simply the *district groups*. The number of district groups and their designation vary from city to city. Typically, a city will divide its territory into four primary district groups: (a) residential district group, (b) commercial district group, (c) industrial district group, and (d) special-purpose districts.

Each district group is subdivided into several districts. For instance, the residential district group may be divided into: one-family, detached residential district; one- and two-family detached and semidetached residential district; and so on. Each residential district may be further subdivided into sub-districts. For example, a one-family detached residential district may be subdivided into: low-density detached single-family district (large-size lots), moderate-density detached single-family district (intermediate-size lots); and so on.

ZONING MAP AND ZONING TEXT

To accomplish its land-use objectives, a zoning ordinance consists of two components: a zoning map and a zoning text. A *zoning map* is based on a comprehensive master plan of the city that takes into account the present and future use of land under the city's jurisdiction. The map shows the district to which a parcel of land belongs, and the *zoning text* specifies the types of buildings that can be built in that district. For instance, in a single-family dwelling district, the zoning ordinance will permit the construction of single-family residences and several other facilities that may be needed in that district, such as fire stations, local houses of worship, schools, recreation centers, playgrounds, parks, and so on.

The zoning text (as distinct from the graphical component—the zoning map) forms the bulk of the zoning ordinance. In addition to specifying the land use, a zoning text also gives the development standards for the city's land. These standards include the maximum ground coverage, maximum floor area ratio, minimum setbacks, maximum height, and number of stories that may be built on a piece of land. Several cities regulate the types of exterior building envelope materials.

Ground Coverage refers to the maximum percentage of land area that may be covered by the building (building's footprint). For instance, for an office building in a downtown area, the ground coverage permitted may be as high as 100%, whereas for a single-family dwelling in a suburban location, the maximum ground coverage may be as low as 15%.

Floor Area Ratio (FAR) refers to the total built-up area (sum of the built-up areas on all floors) divided by the total land area. An FAR of 2.0 means that the total allowable built-up area of the building on all floors is equal to twice the land area. Thus, an FAR of 2.0 is achieved by a two-story building covering the entire piece of land, or a four-story building covering 50% of the land area, and so on. Figure 2.21 gives a graphic explanation of ground coverage, FAR, and setbacks.

Ground coverage and FAR are powerful zoning restrictions that control the overall volume of buildings in a district without greatly jeopardizing design freedom. Volume control is an indirect means of aesthetic control of the development. It also controls population density, traffic volume, environmental pollution, and open spaces.

Restrictions placed on the height or the number of stories under a zoning ordinance also affect population density and traffic volume in the same way as ground coverage and FAR, but the main purpose of height restriction is to ensure that the buildings are within the capabilities of fire-fighting equipment of the city. In some cities, height restrictions may be imposed to maintain views of existing buildings or to preserve the aesthetic character of a district (e.g., in a historic preservation district).

Setbacks refer to the distances a building must be set back from lot lines, thereby specifying the minimum sizes of open areas around the building. Historically, the purpose of a front setback was to reserve land for any future widening of the street. In modern times, setbacks provide greater privacy, help to insulate buildings from traffic noise and fumes, and otherwise enhance the aesthetic appeal of neighborhoods.

ZONING AND PLANNING COMMISSION OF A CITY

The formulation and enforcement of a zoning ordinance are usually delegated by the state to local authorities. Like the building code, the zoning ordinance is enforced under the police powers of the state.

Each local authority has several decision-making bodies that contribute to the formulation and review of the zoning ordinance. Theoretically, the city council is the highest zoning ordinance authority. For practical purposes, however, the zoning ordinance is under the charge of the *zoning and planning commission* of the city, which is typically a body consisting of several local citizens. The responsibilities of this commission include the formulation, development, and review of the zoning plan.

The zoning commission is (ideally) composed of individuals who have distinguished themselves by demonstrating outstanding and unselfish interest in civic affairs. They are appointed by the city council to serve for a fixed term and receive no remuneration for their work.

The initial formulation and subsequent reviews of the city's zoning plan by the zoning commission must go through a public hearing process. This allows all citizens to participate in city planning and the zoning decision-making process.

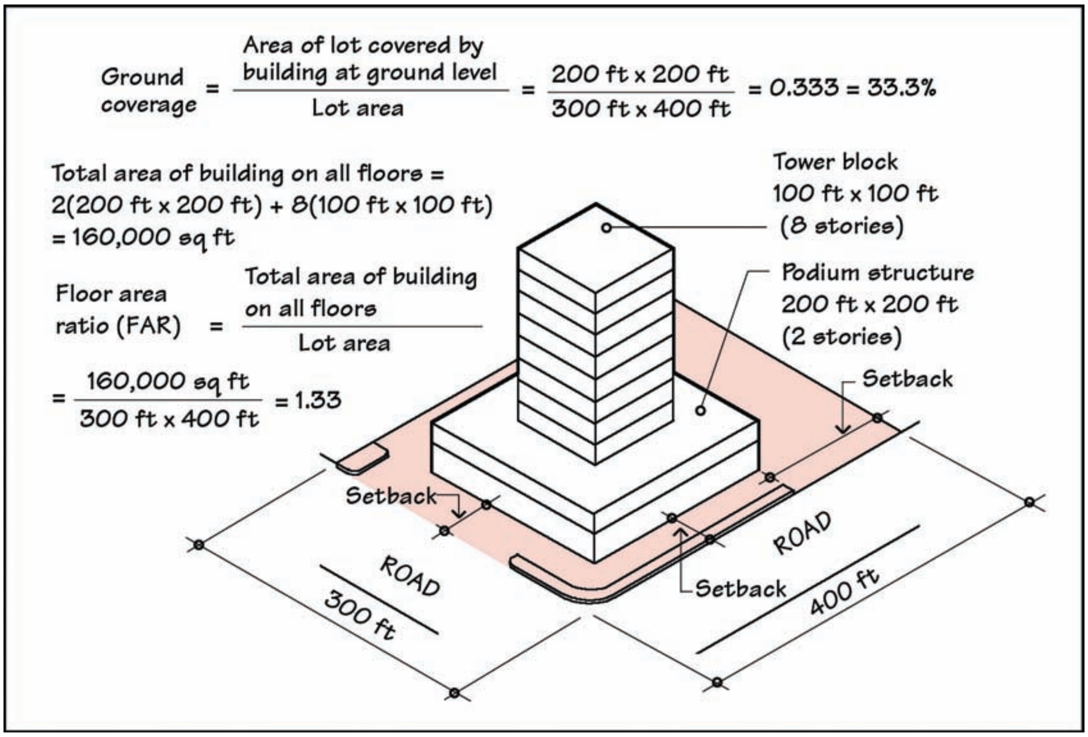

Ground coverage = Area of lot covered by building at ground level / Lot area = 200 ft x 200 ft / 300 ft x 400 ft = 0.333 = 33.3%
Total area of building on all floors = 2(200 ft x 200 ft) + 8(100 ft x 100 ft) = 160,000 sq ft
Floor area ratio (FAR) = Total area of building on all floors / Lot area
= 160,000 sq ft / 300 ft x 400 ft = 1.33
Tower block
100 ft x 100 ft
(8 stories)
Podium structure
200 ft x 200 ft
(2 stories)
Setback
Setback
Setback
ROAD
ROAD
300 ft
400 ft

FIGURE 2.21 The terms ground coverage, floor area ratio, and setback are illustrated.

Although the zoning commission and the city council are the bodies responsible for zonal plan review, the day-to-day work related to zoning administration is carried out by the city's planning department. Thus, the owner of a piece of land who desires to rezone (i.e., change the land use) the property would submit the request to the city's planning department, which would review it, make a recommendation, and forward it to the zoning commission for a decision.

If the zoning commission agrees to rezoning, a public hearing is arranged. After the public hearing, the zoning commission makes its decision, which is usually in the form of a recommendation to the city council. The city council may support the zoning commission's recommendation or hold its own public hearing on the matter before voting.

BOARD OF ZONING APPEALS (BOARD OF ADJUSTMENT)

The implementation of land use control involves more than a mere formulation or review of the zoning plan. It also involves the enforcement of zoning ordinances that give rise to problems of application and interpretation. These problems are referred to the board of zoning appeals, also called the *board of adjustment*. This board consists of several members, usually appointed by the mayor or the city council.

The primary responsibility of the board of adjustment is to hear appeals on actions taken by city officials who administer zoning regulations and to make special exceptions to zoning regulations. Special exceptions generally refer to granting variances to setbacks, ground coverage, FAR, and so on, whose literal enforcement may cause unnecessary and undue hardship to the owner. Variances granted by the board must not be contrary to the public interest and must not act to relieve the owner of self-created hardship. The meetings of the board are open to the public.

2.13 BUILDING'S ACCESSIBILITY—AMERICANS WITH DISABILITIES ACT (ADA)

The Americans with Disabilities Act (ADA) is a 1990 federal law that came into effect in January 1992. The objective of the act is to ensure equal opportunity to individuals with disabilities. It is a comprehensive legislation that addresses four major concerns:

Title I pertains to employment discrimination against individuals with disabilities.

Title II refers to the accessibility of public transportation lines, such as railroads and buses.

Title III deals with accessibility in buildings, including accessible routes to and from parking areas, and from one building to the other on the same site.

Title IV covers accessible telecommunication facilities, such as telephones for the hearing impaired or individuals with other handicaps, and automatic teller machines.

Only Title III and Title IV are of concern in the design of buildings. Title III is more pertinent as it regulates access to buildings so that they are usable with equal ease by all building occupants and visitors, including individuals with disabilities (of mobility, hearing, seeing, and physical stature). The act requires that all new construction and alterations to existing construction provide barrier-free access routes on the site, into, and within all building spaces. Single-family dwellings, multifamily dwellings, and buildings funded by religious organizations, such as churches and temples, are exempt from ADA's accessibility provisions.

ADA's Title III requirements relate to the design of entrances, doors, stairways, ramps, changes of level, sidewalks, elevators, light switches, window hardware, drinking fountains, toilet facilities, door width, doorknobs, and so on. The requirements are detailed in ADA *Standard for Accessible Design* (ADASAD) and ADA *Accessibility Design Guidelines* (ADAAG). Figure 2.22 illustrates just one instance of where ADA is applicable—the accessibility of an elevator control panel.

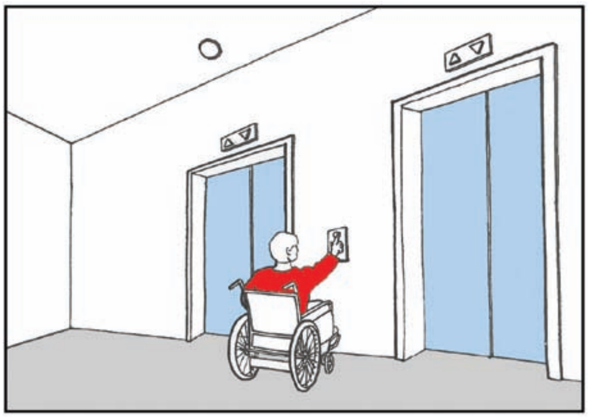


FIGURE 2.22 Apart from several other requirements, accessibility in buildings includes the accessibility of control mechanisms of elevators (as shown), light switches, window hardware, thermostats, and so on per the reach range specified in ADASAD.

ENFORCEMENT OF ADA ACCESSIBILITY REQUIREMENTS

Because ADA is a federal legislation, it is enforced like other civil rights laws—through litigation in federal courts. In other words, its enforcement comes up only when a lawsuit is filed against an erring building owner, that is, in a post-occupancy situation. As this can cause much hardship to building owners including the states and cities (for state- and city-owned buildings), the states have formulated their own accessibility standards that either meet or exceed ADASAD, and are enforced by the states.

For example, ADA Title III and Title IV provisions in Texas are enforced using Texas Accessibility Standard (TAS) through procedures set up by Texas Department of Licensing and Regulation (TDLR). The building official's office does not review construction documents for conformance with TAS, but requires confirmation from TDLR for review and certification before issuing building permit. Buildings costing less than $50,000 are, however, reviewed by the building official's office. Other states follow similar procedures.

This procedure does not imply delegation of ADA enforcement authority to the states, nor does it take away an individual's right to seek relief in the federal courts, but substantially reduces the risk to owners for having exercised due diligence. It is of interest to note that the International Building Code has an entire chapter devoted to accessibility, which though similar in provisions to ADASAD, is not identical. Therefore, it is not currently used.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

25. A prescriptive code needs no standards.
  a. True **b.** False

26. The construction standards used in building codes are produced by
  a. trade associations.
  b. professional societies.
  c. governmental organizations.
  d. standards writing organizations.
  e. all of the above.

27. Which of the following is not a standards writing organization?
  a. ASTM **b.** NSF
  c. UL **d.** ANSI

28. Which of the following is the largest standards writing organization?
  a. NRCA **b.** ANSI
  c. UL **d.** ASTM
  e. ASCE

29. The acronym UL stands for
  a. Universal Laboratories.
  b. Underwriters Laboratories.
  c. United Legislature.
  d. Union of Laborers.

30. A zoning ordinance refers to regulations that pertain mainly to
  a. the use of buildings within the city.
  b. the use of highways within the city.
  c. the use of land within the city.
  d. none of the above.

31. A zoning ordinance consists of
  a. the zoning map of the city.
  b. the zoning map and the building code of the city.
  c. the zoning text and the building code of the city.
  d. the zoning text and the zoning map of the city.
  e. the zoning text, zoning map, and the building code of the city.

32. The term FAR refers to
  a. factory area restrictions. **b.** floors as required.
  c. floor area ratio. **d.** none of the above.

33. If the total area of a lot is 15,000 ft^2 and the total covered area on all floors of the building on this lot is 60,000 ft^2, the FAR for the property is
  a. 0.25. **b.** 1.5.
  c. 6.0. **d.** 3.7.
  e. none of the above.

34. The Americans with Disabilities Act (ADA) is devoted entirely to provisions relating to accessibility within a building.
  a. True **b.** False

35. Before granting the building permit, the office of the building official of a jurisdiction must review the construction documents of the building for conformance with
  a. the accessibility requirements of the jurisdiction's building code.
  b. the requirements of the Americans with Disabilities ACT (ADA) passed by the federal government
  c. either (a) or (b) depending on the jurisdiction.
  d. none of the above.

PRINCIPLES IN PRACTICE

Building Code Analysis—A Part of Construction Documents

As stated in Section 2.2, construction documents (CD) of a proposed building are reviewed by the jurisdiction before granting the building permit. Therefore, the CD set includes complete, clear, and concise analysis of the building code to explain to the jurisdiction that the proposed building meets with all applicable building code requirements. In fact, the first few drawings (sheets) of the CD set, immediately after the index sheet(s), pertain to code analysis.

The code analysis drawings typically indicate the building's occupancy classification, type of construction, type of automatic sprinklers (if any), means-of-egress system, exit locations, and so on. One of the most important aspects of the analysis is the calculation of maximum allowable area, maximum allowable height, and maximum allowable number of stories of the building. This section gives a brief account of the these calculations based on the International Building Code.

(Continued)

PRINCIPLES IN PRACTICE

AREA, HEIGHT, AND NUMBER OF STORIES OF A PROPOSED BUILDING AND BUILDING CODE REQUIREMENTS

Before proceeding to design development or the construction document stage, the architect must establish that the proposed design meets with building code's provisions on: (a) the maximum allowable area of the building, (b) maximum allowable height, and (c) maximum allowable number of stories. These three building attributes are a function of the following four factors:

- Building's occupancy classification.
- Building's type of construction.
- Width of accessible open spaces around the building (frontage).
- Whether or not the building is provided throughout with automatic sprinklers.

These calculations can be involved for some buildings. The description presented here is for relatively less complicated situations. The reader is advised to go through the following description and then work through the examples and return to the description to get a comprehensive understanding of the subject. The following six-step approach should help to simplify the process.

Step 1. Occupancy Classification and Type of Construction
Determine the building's occupancy classification and type of construction.

Step 2. Height of Building
Verify that the height of the proposed building ≤ the maximum allowable height per the building code, Table 2.3.

Step 3. Number of Stories
Verify that the number of stories of the proposed building ≤ the maximum number of stories per the building code, Table 2.4.

Step 4. Allowable Area Factor, A_t
Read the allowable area factor, A_t, of the building from Table 2.5. A_t is a function of whether the building is nonsprinklered, sprinklered, and whether it is a one-story or a multistory building, that is, A_t is a function of : NS (nonsprinklered), S1 (sprinklered, one-story), or SM (sprinklered, multistory).

TABLE 2.3 MAXIMUM ALLOWABLE HEIGHT OF A BUILDING ABOVE GRADE PLANE* FOR SELECTED OCCUPANCIES AND TYPES OF CONSTRUCTION

Occupancy Classification	Sprinklered or nonsprinklered; One story or multiple stories	Type of Construction						
		I(A)	I(B)	II(A)	II(B)		V(A)	V(B)
A, B, E, F, M, S, and U	**NS** **Nonsprinklered**; ≥ 1-story building	↑ UL	160 ft	65 ft	55 ft		50 ft	40 ft
	S **Sprinklered**; ≥ 1-story building	↑ UL	180 ft	85 ft	75 ft		70 ft	60 ft

1. The information given in this table is incomplete. Occupancy groups (H, I, and R) and types of construction (Types III-A, III-B, and IV) are not included here. See the reference given below for complete information.
2. The occupancy classifications shown in the first column (A, B, E, etc.) include all divisions corresponding to the stated occupancy.
3. UL = unlimited height allowed by the IBC. A city's zoning code may place limits on the building's height based on fire-fighting and rescue resources available with the city.
4. S = sprinklered building (with NFPA 13 automatic sprinkler system).
5. NS = nonsprinklered building.

* Grade plane is essentially the finished ground level abutting the exterior walls of the building. Where the finished ground level varies, the grade plane is the imaginary horizontal plane representing the average finished ground level.

Reference: 2015 International Building Code (IBC), p. 98.

TABLE 2.4 MAXIMUM ALLOWABLE NUMBER OF STORIES OF A BUILDING ABOVE GRADE PLANE* FOR SELECTED OCCUPANCIES AND TYPES OF CONSTRUCTION

Occupancy Classification	Sprinklered or nonsprinklered; One story or multiple stories	Type of Construction					
		I(A)	I(B)	II(A)	II(B)	V(A)	V(B)
A-3	**NS** **Nonsprinklered**; ≥ 1-story building	UL	11 stories	3 stories	2 stories	2 stories	1 story
	S **Sprinklered**; ≥ 1-story building	UL	12 stories	4 stories	3 stories	3 stories	2 stories
B	**NS** **Nonsprinklered**; ≥ 1-story building	UL	11 stories	5 stories	3 stories	3 stories	2 stories
	S **Sprinklered**; ≥ 1-story building	UL	12 stories	6 stories	4 stories	4 stories	3 stories
S-1	**NS** **Nonsprinklered**; ≥ 1-story building	UL	11 stories	4 stories	2 stories	3 stories	1 story
	S **Sprinklered**; ≥ 1-story building	UL	12 stories	5 stories	3 stories	3 stories	2 stories

1. The information given in this table is incomplete. Types of construction (Types III-A, III-B, and IV) and several occupancies are not included here. See the reference given below for complete information.
2. UL = unlimited number of stories allowed by the IBC. A city's zoning code may place limits on the number of stories based on fire-fighting and rescue resources available with the city.
3. S = sprinklered building (with NFPA 13 automatic sprinkler system, see Section 7.11).
4. NS = nonsprinklered building.

* Grade plane is essentially the finished ground level abutting the exterior walls of the building. Where the finished ground level varies, the grade plane is the imaginary horizontal plane representing the average finished ground level.

Reference: 2015 International Building Code (IBC), p. 99.

Step 5. Frontage Increase Factor, I_f

The frontage increase factor, I_f, is a measure of the increase in the allowable area on account of open spaces surrounding the building. Its value is given by the following equation:

$$\boxed{I_f = \left[\frac{F}{P} - 0.25\right]\left(\frac{W}{30}\right)} \qquad \textbf{Eq. (2.1)}$$

(a) Definition of W in Equation (2.1)

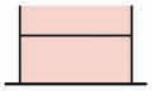
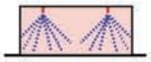
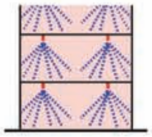
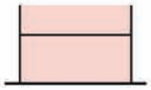
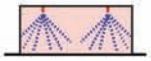
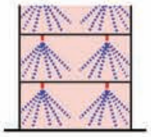
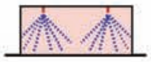
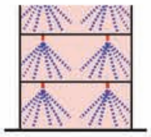
W = width of the public way or an "accessible" open space within the lot, not less than 20-ft wide. Thus, if an open space is less than 20-ft wide, its width is assumed as zero. The term "accessible" means that the open space within the lot is accessible either directly to the public way or through a minimum 20-ft wide space within the lot.

(Continued)

PRINCIPLES IN PRACTICE

Building Code Analysis—A Part of Construction Documents (*Continued*)

TABLE 2.5 ALLOWABLE AREA FACTOR (A_t) OF A BUILDING ABOVE GRADE PLANE* FOR SELECTED OCCUPANCIES AND TYPES OF CONSTRUCTION

Occupancy Classification	**Sprinklered or nonsprinklered; One story or multiple stories**	**Type of Construction**						
		I(A)	**I(B)**	**II(A)**	**II(B)**		**V(A)**	**V(B)**
A-3	**NS** **Nonsprinklered**; 1-story or ≥ 2-story building 	Unlimited area	Unlimited area	15,500 sq ft	9,500 sq ft		11,500 sq ft	6,000 sq ft
	S1 **Sprinklered**; 1-story building 	Unlimited area	Unlimited area	62,000 sq ft	38,000 sq ft		46,000 sq ft	24,000 sq ft
	SM **Sprinklered**; ≥ 2-story building 	Unlimited area	Unlimited area	46,500 sq ft	28,500 sq ft		34,500 sq ft	18,000 sq ft
B	**NS** **Nonsprinklered**; 1-story or ≥ 2-story building 	Unlimited area	Unlimited area	37,500 sq ft	23,000 sq ft		18,000 sq ft	9,000 sq ft
	S1 **Sprinklered**; 1-story building 	Unlimited area	Unlimited area	150,000 sq ft	92,000 sq ft		72,000 sq ft	36,000 sq ft
	SM **Sprinklered**; ≥ 2-story building 	Unlimited area	Unlimited area	112,500 sq ft	69,000 sq ft		54,000 sq ft	27,000 sq ft
S-1	**NS** **Nonsprinklered**; 1-story or ≥ 2-story building	Unlimited area	48,000 sq ft	26,000 sq ft	17,500 sq ft		14,000 sq ft	9,000 sq ft
	S1 **Sprinklered**; 1-story building 	Unlimited area	192,000 sq ft	104,000 sq ft	70,000 sq ft		56,000 sq ft	36,000 sq ft
	SM **Sprinklered**; ≥ 2-story building 	Unlimited area	144,000 sq ft	78,000 sq ft	52,500 sq ft		42,000 sq ft	27,000 sq ft

1. The information given in this table is incomplete. Types of construction (Types III-A, III-B, and IV) and several occupancies are not included here. See the reference given below for complete information.
2. S1 = sprinklered one-story building; SM = sprinklered multistory building (two or more stories); Sprinklers to conform with NFPA 13 automatic sprinkler system, see Section 7.11.
3. NS = nonsprinklered building, regardless of the number of stories in the building.

* Grade plane is essentially the finished ground level abutting the exterior walls of the building. Where the finished ground level varies, the grade plane is the imaginary horizontal plane representing the average finished ground level.

Reference: 2015 International Building Code (IBC), p. 102.

PRINCIPLES IN PRACTICE

Thus, with reference to the layout plan of Figure 2.23, the value of W for the open space to the left side of the building is zero because being 15-ft wide, it is <20 ft. The same applies to the open space to the right side of the building, being 18-ft wide. It also applies to 35-ft-wide open space at the rear of the building because it is not accessible to a public way. The reason is that the open spaces (15-ft and 18-ft wide) that provide access to the rear are both less than 20-ft wide. In other words, the width of open space at the rear of the building, W is zero.

If a W-value ≥ 30 ft, set that W-value $= 30$ ft. This means that an open space >30-ft wide does not yield an increase in the value of I_f.

If the values of W vary along the building's perimeter, set $W =$ weighted average $= W_{av}$ in Equation (2.1), as given by the following expression.

$$\boxed{W = W_{av} = \frac{L_1(W_1) + L_2(W_2) + \cdots}{L_1 + L_2 + \cdots}} \qquad \textbf{Eq. (2.2)}$$

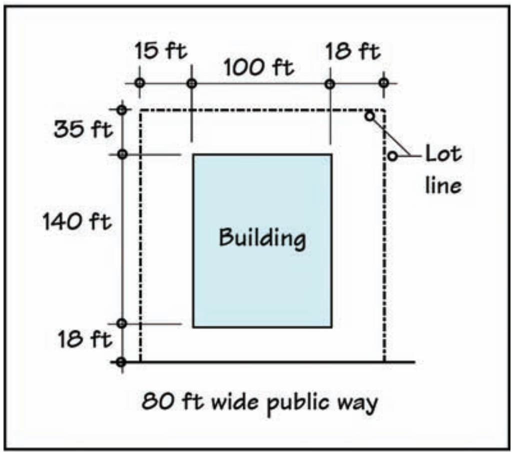


FIGURE 2.23 Site layout plan (not to scale) of a building, refers to Example 2.1.

Where, W_1, W_2, etc. $=$ width of open space fronting each part of the building's perimeter. L_1, L_2, etc. $=$ length of each part of building's perimeter corresponding to W_1, W_2, . . . , respectively.

(b) Definition of L_1, L_2, etc. in Equation (2.2)

If any W-value < 20 ft, set that W-value equal to zero, and the corresponding L-value also equal to zero. If a W-value ≥ 20 ft, the corresponding L-value is its actual L-value. For example, if $W_3 = 22$ ft, and $L_3 = 110$ ft, then $L_3 = 110$ ft.

If any W-value ≥ 30 ft, it is set equal to 30 ft, and the corresponding L-value is its actual value because the W-value >20 ft.

Note that the entire width of public way is included as the width of open space in front of the building, not just the open space within the lot. For example, the width of open space in the front of the building in Figure 2.23 is 98 ft, not 18 ft. Because the open space exceeds 30 ft, it is set equal to 30 ft.

Again with reference to Figure 2.23, the values of W and L are as follows:

$W_1 = 30$ ft (the actual value $= 98$ ft); $L_1 = 100$ ft.
$W_2 = 0$ (actual value $= 15$ ft <20 ft). Because $W_2 = 0$, $L_2 = 0$.
$W_3 = 0$ (actual value $= 35$ ft, but is not accessible). Because $W_3 = 0$, $L_3 = 0$.
$W_4 = 0$ (actual value $= 15$ ft <20 ft). Because $W_4 = 0$, $L_4 = 0$.

Substituting the L-values and W-values in Equation (2.2), we obtain $W_{av} = 30$ ft for the layout plan of Figure 2.23.

(c) Definition of F in Equation (2.1)

$F =$ the sum of the parts of the building's perimeter that front on a public way $\geq$20-ft wide or an accessible open space within the lot ≥ 20-ft wide. Thus,

$$F = L_1 + L_2 + L_3 + \cdots$$

In this expression for F, the value of $L = 0$ (if the corresponding W-value $<$20 ft). If a W-value $\geq$20 ft, the corresponding L-value $=$ actual value of L. Thus, for the layout plan of Figure 2.23,

$$F = L_1 + L_2 + L_3 + L_4 = 100 + 0 + 0 + 0 = 100 \text{ ft}$$

(d) Definition of P in Equation (2.1)

$P =$ perimeter of the entire building. In calculating the value of P, the actual L-values are used (no modifications). Thus, with reference to Figure 2.23, $P = 100 + 140 + 100 + 140 = 480$ ft.

If $(F/P) < 0.25$, it is to be set equal to 0.25 in Equation (2.1), which gives $I_f = 0$.

EXAMPLE 2.1 (CALCULATION OF FRONTAGE INCREASE FACTOR, I_f)

Determine the value of I_f for the site layout plan of Figure 2.23.

SOLUTION

The width of open spaces (W_1, W_2, W_3, and W_4) around the building are 98 ft, 15 ft, 35 ft, and 18 ft, respectively. $W = W_{av} = 30$ ft (previously calculated).

(Continued)

PRINCIPLES IN PRACTICE

Building Code Analysis—A Part of Construction Documents (*Continued*)

$F = 100$ ft (previously calculated)

$P = 480$ ft (previously calculated)

$$\frac{F}{P} = \frac{100}{480} = 0.21$$

Because $(F/P) < 0.25$, $I_f = 0$ (see the definition of P).

EXAMPLE 2.2 (CALCULATION OF FRONTAGE INCREASE FACTOR, I_f)

Determine the value of I_f for the two site layout plans of Figure 2.24.

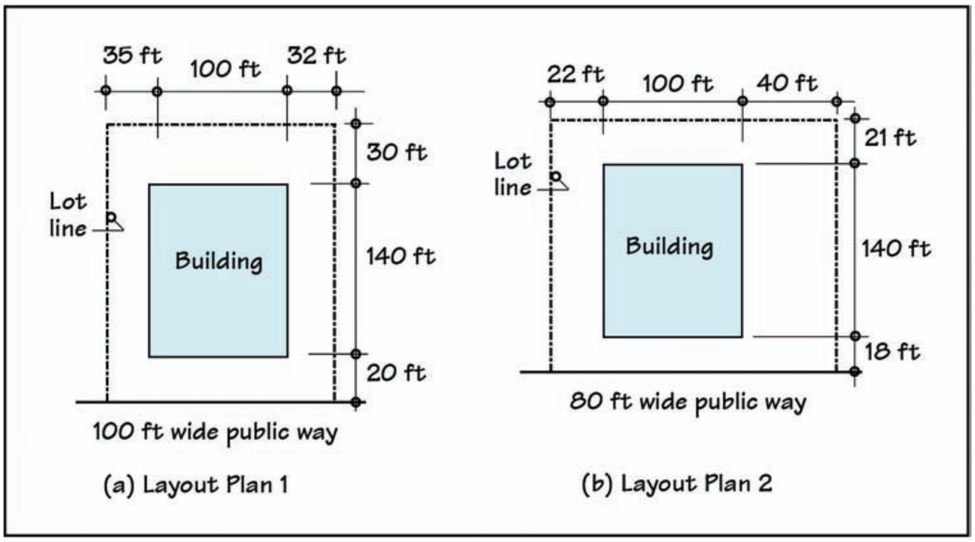

35 ft
100 ft
32 ft
30 ft
Lot line
Building
140 ft
20 ft
100 ft wide public way
(a) Layout Plan 1
22 ft
100 ft
40 ft
21 ft
Lot line
Building
140 ft
18 ft
80 ft wide public way
(b) Layout Plan 2

FIGURE 2.24 Site layout plans (not to scale) of buildings, refers to Example 2.2.

SOLUTION

Layout Plan 1: With reference to Figure 2.24(a), the W-values (W_1, W_2, W_3, and W_4) are 120 ft, 35 ft, 30 ft, and 32 ft, respectively. Because all W-values ≥ 30 ft, $W_1 = W_2 = W_3 = W_4 = 30$ ft. Hence, $W = W_{av} = 30$ ft. Because all W-values are ≥ 20 ft, the corresponding L-values are their actual values. Therefore,

$$F = L_1 + L_2 + L_3 + L_4 = 100 + 140 + 100 + 140 = 480 \text{ ft}$$

$$P = 480 \text{ ft}$$

$$\frac{F}{P} = \frac{480}{480} = 1.0$$

From Equation (2.1),

$$I_f = [1.0 - 0.25]\frac{30}{30} = 0.75$$

Note that $I_f = 0.75$ is the maximum possible value of I_f.

Layout Plan 2: With reference to Figure 2.24(b), W_1, W_2, W_3, and W_4 are 88 ft, 22 ft, 21 ft, and 40 ft, respectively. Setting W-values ≥ 30 ft equal to 30 ft, the effective W-values are:

$W_1 = 30$ ft, $W_2 = 22$ ft, $W_3 = 21$ ft, and $W_4 = 30$ ft. Because all W-values are ≥ 20 ft, the corresponding L-values are their actual values. Therefore,

$L_1 = 100$ ft, $L_2 = 140$ ft, $L_3 = 100$ ft, and $L_4 = 140$ ft. From Equation (2.2),

$$W = W_{av} = \left[\frac{100(30) + 140(22) + 100(21) + 140(30)}{100 + 140 + 100 + 140}\right] = 25.8 \text{ ft}$$

$$F = L_1 + L_2 + L_3 + L_4 = 100 + 140 + 100 + 140 = 480 \text{ ft}$$

$$P = 480 \text{ ft}$$

$$\frac{F}{P} = \frac{480}{480} = 1.0$$

From Equation (2.1)

$$I_f = [1.0 - 0.25]\frac{25.8}{30} = 0.65$$

Step 6(a). Maximum Allowable Area for a One-Story Building, A_a

The maximum allowable area, A_a, for a one-story building is obtained from the following equation.

$$\boxed{A_a = A_t + (NS)I_f} \qquad \textbf{Eq. (2.3)}$$

Where, NS = allowable area factor, obtained from Table 2.5, for a nonsprinklered building regardless of whether the building is sprinklered or not. The value of A_t is also obtained from Table 2.5 corresponding to S1 if the building is sprinklered. If the building is nonsprinklered, the value of A_t corresponds to NS, in which case, $A_t = NS$.

For example, consider a one-story building of Occupancy B and Type II(A) construction. If this building is nonsprinklered, the value of A_t from Table 2.5 = 37,500 sq ft. The value of NS is also obtained from the same table = 37,500 sq ft. If this building is sprinklered, A_t = 150,000 sq ft (corresponding to S1) and NS = 37,500 sq ft.

Step 6(b). Maximum Allowable Area per Story of a Multistory Building, A_{ps}

The maximum allowable area per story of a multistory building (≥2 stories), A_{ps}, is obtained from the following equation.

$$\boxed{A_{ps} = [A_t + (NS)I_f]S_a} \qquad \textbf{Eq. (2.4)}$$

Where, NS = allowable area factor, obtained from Table 2.5, for a nonsprinklered building regardless of whether the building is sprinklered or not. A_t is also obtained from Table 2.5 corresponding to SM. $S_a = 1$ because we are interested in the allowable area per story.

Step 6(c). Maximum Allowable Area for the Entire Multistory Building, A_a

The maximum allowable area (aggregate area on all stories), A_a, is also obtained from Equation (2.4) by substituting $S_a = 2$ for a two-story building, and $S_a = 3$ for a building with ≥3 stories.

EXAMPLE 2.3 (ALLOWABLE AREA OF A NONSPRINKLERED, ONE-STORY BUILDING)

Determine if the layout plan of the furniture warehouse shown in Figure 2.25 meets the building code provisions on allowable area and height. The building is one story high (total height = 30 ft), and the type of construction proposed is Type II(B). No automatic sprinklers are provided.

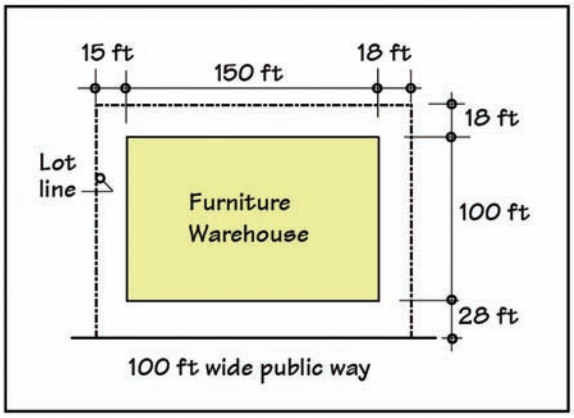


FIGURE 2.25 Site layout plan (not to scale) of a furniture warehouse, refers to Example 2.3.

SOLUTION

Step 1: A furniture warehouse is Occupancy S-1 (Table 2.1). Type of Construction is Type II(B), per proposed design.

Step 2: Height of proposed building = 30 ft < maximum allowable height for a nonsprinklered building (= 55 ft, Table 2.3). So the height is OK. (Note that the term OK is a commonly used technical jargon, implying conformance with the requirements of applicable provision of code or standard.)

Step 3: Number of stories of proposed building = 1. Maximum allowable number of stories = 2 (Table 2.4), which is OK.

Step 4: Allowable area factor, A_t

A_t = 17,500 sq ft (corresponds to NS in Table 2.5 because the building is nonsprinklered)

Step 5: Frontage increase factor, I_f

(Continued)

PRINCIPLES IN PRACTICE

Building Code Analysis—a Part of Construction Documents (*Continued*)

Only one (100 ft) side of the building fronts a public way, Figure 2.25. Because the other three open spaces are less than 20 ft wide, they do not count as accessible open spaces. Hence,

$$F = 150 \text{ ft}$$
$$P = 150 + 100 + 150 + 100 = 500 \text{ ft}$$

Hence, $(F/P) = (100/500) = 0.2$. Because $(F/P) < 0.25$, $I_f = 0$.

Step 6: Maximum allowable area for the entire building, A_a from Equation (2.3),

$$A_a = A_t + (NS)I_f = 17{,}500 + 17{,}500(0) = 17{,}500 \text{ sq ft}$$

The area provided is $150(100) = 15{,}000$ sq ft, which is less than the allowable area of 17,500 sq ft. Therefore, the area provided is OK.

EXAMPLE 2.4 (ALLOWABLE AREA OF A SPRINKLERED, MULTISTORY BUILDING)

An architect's proposal for a six-story office building (80 ft tall) is shown in the site plan of Figure 2.26. Determine if the area, height, and number of stories of the building conform with the building code. The type of construction proposed is Type II(A), and the building is provided throughout with an approved automatic sprinkler system.

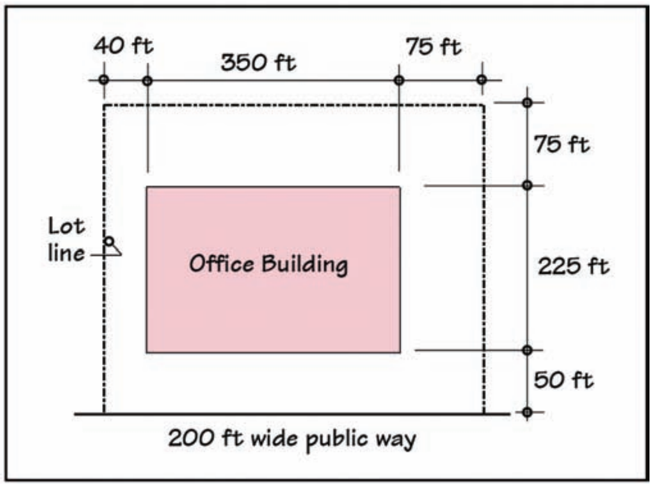


FIGURE 2.26 Site layout plan (not to scale) of an office building, refers to Example 2.4.

SOLUTION

Step 1: An office building is Occupancy B (Table 2.1). Type of Construction is Type II(A), per proposed design.

Step 2: Height of proposed building = 80 ft < maximum allowable height for a sprinklered building (=85 ft, Table 2.3), which is OK.

Step 3: Number of stories of proposed building = 6. Maximum allowable number of stories = 6 (Table 2.4), which is OK.

Step 4: Allowable area factor, A_t

$A_t = 112{,}500$ sq ft (corresponds to SM in Table 2.5 because the building is sprinklered, multistory)

Step 5: Frontage increase factor, I_f

With reference to Figure 2.26, the building has open spaces on all four sides, and their widths (W-values) ≥ 20 ft. Hence, all L-values are their actual values. Thus,

$$F = 350 + 225 + 350 + 225 = 1{,}150 \text{ ft}$$
$$P = 1{,}150 \text{ ft}$$

Because $W \geq 30$ ft on all sides of the building, set $W = W_{av} = 30$. From Equation (2.1),

$$I_f = \left[\frac{1{,}150}{1{,}150} - 0.25\right]\left(\frac{30}{30}\right) = 0.75$$

Step 6(a): Maximum allowable area per story, A_{ps}

From Table 2.5, NS = 37,500 sq ft. From Equation (2.4),

$$A_{ps} = [A_t + (NS)I_f]S_a = [112{,}500 + (37{,}500)0.75](1) = 140{,}625 \text{ sq ft}$$

Area provided on each story = 350(225) = 78,750 sq ft < A_{ps}(= 140,625 sq ft). So, it is OK.

Step 6(b): Maximum allowable area on all stories, A_a

S_a = actual number of stories in the building, but not >3. Therefore, $S_a = 3$. From Equation (2.4),

$$A_a = [A_t + (NS)I_f]S_a = [112{,}500 + (37{,}500)0.75](3) = 421{,}875 \text{ sq ft}$$

The aggregate area provided on all stories = 350(225)6 = 472,500 sq ft. Because this exceeds the allowable area (=421,875 sq ft), it is NG. (Note that NG, an acronym for "no good", is a commonly used technical term, like the term OK.)

Thus, the proposed design must be altered either by reducing the area on the sixth story, or by upgrading the type of construction to Type I(B). The reader may note from Table 2.5 that the code allows unlimited area for occupancy B with Type I(B) construction.

PRINCIPLES IN PRACTICE

ALLOWABLE AREA OF A MIXED-OCCUPANCY BUILDING

The allowable area and height determinations given so far refer to a single-occupancy building. For a mixed-occupancy building, two cases must be distinguished (see Section 2.7).

First, if the building is not provided with required occupancy separations (a *nonseparated mixed-occupancy building*), the allowable area and height are calculated by assuming that the entire building belongs to only one occupancy. These calculations are made for each occupancy provided. The smallest area and the smallest height obtained from the calculations are the allowable area and height of the building.

Second, if required occupancy separations have been provided, the building is treated as a *separated mixed-occupancy building*. For such a building, the sum of the respective floor areas provided for each occupancy divided by their allowable areas at each story must not exceed 1.0, as shown in Equation (2.5).

For example, consider a building with three different occupancies. Let us call these occupancies Occupancy 1, Occupancy 2, and Occupancy 3. Assume that the area provided at a story for Occupancy 1 is (A_{pr1}), for Occupancy 2 is (A_{pr2}), and for Occupancy 3 is (A_{pr3}). Assume further that the respective allowable areas for a story for the three occupancies are (A_{al1}), (A_{al2}), and (A_{al3}); then the following equation must be satisfied.

$$\boxed{\frac{A_{pr1}}{A_{al1}} + \frac{A_{pr2}}{A_{al2}} + \frac{A_{pr3}}{A_{al3}} \leq 1.0} \qquad \textbf{Eq. (2.5)}$$

REVIEW QUESTIONS

1. What is the primary purpose of building codes? Explain.
2. What is the difference between a prescriptive and a performance-type code provision? Explain with the help of an example.
3. List the model code organizations that existed in the United States prior to the year 2000 and the building codes published by each.
4. Describe the relationship between a building code and construction standards. List three important standards organizations in the United States.
5. What information can you derive from a given designation of an ASTM standard such as E 119-95a?
6. List the first five steps you will follow in ascertaining that a building conforms to the provisions of the building code.
7. List at least three codes published by the International Code Council.
8. What do the terms *ground coverage* and *floor area ratio* (FAR) mean? Are they part of building code provisions? Explain.
9. What is board of adjustment? Explain.
10. What are the responsibilities of a zoning and planning commission of a city?
11. Show that the value of I_f for the building of Figure 2.27 is 0.71.
12. If in the layout plan of Figure 2.27, the rear setback is changed to 35 ft (in place of 100 ft) and all else remains the same as shown, what will be the revised value of I_f? Explain.
13. Show that the value of I_f in the layout plan of Figure 2.27 is 0.54 if the left-side setback is changed to 15 ft (in place of 22 ft) and all else remains the same as shown.
14. Show that the maximum allowable area per story of the building of Figure 2.27 is 35,245 sq ft, assuming that the building is fully sprinklered and $I_f = 0.71$.

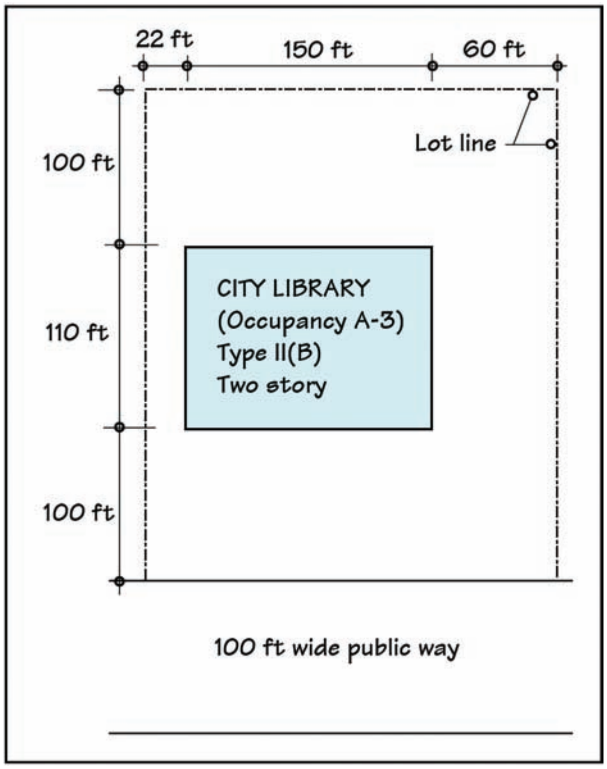


FIGURE 2.27 Layout plan (not to scale) of a library building, refers to "Review Questions 11 to 14".

CHAPTER 3

Loads on Buildings

CHAPTER OUTLINE

3.1 DEAD LOADS
3.2 LIVE LOADS
3.3 RAIN LOAD
3.4 WIND LOAD BASICS
3.5 FACTORS THAT AFFECT WIND LOADS
3.6 ROOF SNOW LOAD
3.7 EARTHQUAKE LOAD
3.8 FACTORS THAT AFFECT EARTHQUAKE LOADS
3.9 WIND VERSUS EARTHQUAKE RESISTANCE OF BUILDINGS
PRINCIPLES IN PRACTICE: DEAD LOAD AND LIVE LOAD ESTIMATION

Buildings are subjected to several types of loads, Figure 3.1. Two main classifications of loads are

- Gravity loads
- Lateral loads

Gravity loads are caused by the gravitational pull of the earth and act in the vertical direction. Therefore, they are also referred to as *vertical loads*. Gravity loads include the materials and components that comprise the buildings, as well as people, rainwater, snow, furniture, equipment, and all that is contained within the building. Gravity loads are further classified as *dead loads* and *live loads*, as explained in subsequent sections.

The two primary sources of *lateral loads* on buildings are wind and earthquakes. The effect of each is to create loads in the lateral (other than vertically downward) direction. For example, wind creates horizontal forces on a wall as well as vertically upward forces (suction) on a flat roof. The main effect of earthquake ground motion is to create horizontal forces in buildings, although a small amount of vertical force may also exist. Additional examples of lateral loads are earth pressure on basement walls, water pressure on tank walls, and loads caused by blasts and moving vehicles or equipment.

In this chapter, we examine the nature of different types of loads on buildings. The treatment given here is brief and qualitative and sets the stage for a detailed investigation of the topic by an interested reader.

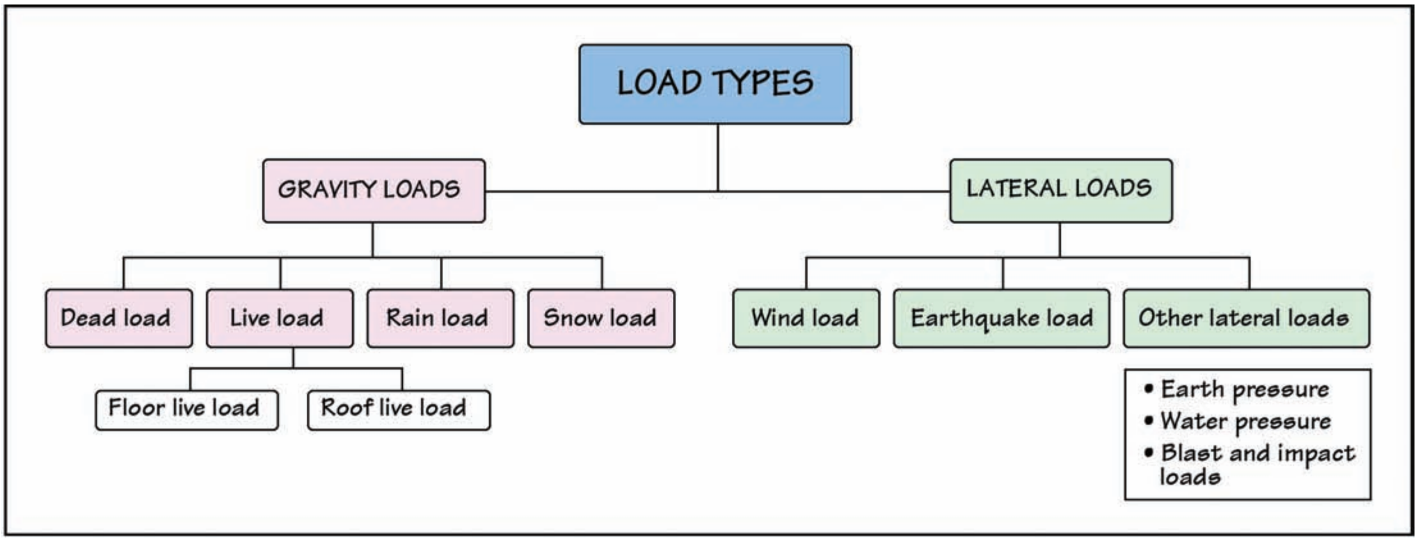


FIGURE 3.1 Some of the important loads in buildings.

Units of Measurement for Loads

In the U.S. system of units, a load is expressed in pounds (lb). The pound is a small unit for measuring building loads. Therefore, the unit kilopound (kip) is commonly used; 1 kip is equal to 1,000 lb. Thus, 2.5 kips = 2,500 lb.

When the load is distributed over a surface such as a floor or roof, it is generally expressed in pounds per square foot (psf), Figure 3.2. A beam is treated as a linear element, because its width is generally much smaller than its length. Therefore, the load on a beam is generally expressed in terms of pounds per foot length of the beam (lb/ft). If the load on the beam is large, it is generally stated as kilopounds per foot (kips/ft). The load on a column is expressed in terms of pounds (lb) or kilopounds (kips).

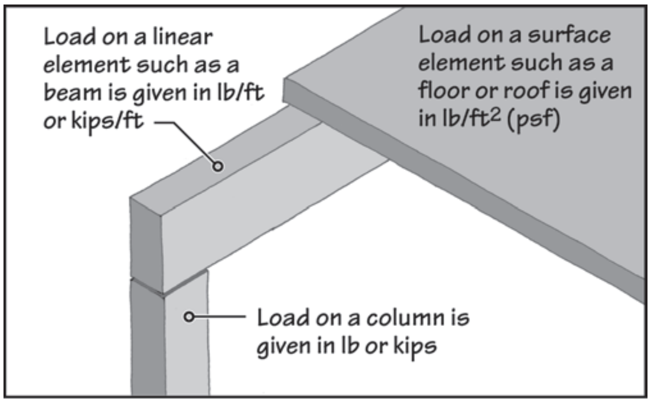

Load on a linear element such as a beam is given in lb/ft or kips/ft
Load on a surface element such as a floor or roof is given in lb/ft^2 (psf)
Load on a column is given in lb or kips

FIGURE 3.2 The loads on various elements of a building are expressed in different units.

3.1 DEAD LOADS

Dead loads are always present in a building; that is, they do not vary with time. They include the weights of the materials and components that comprise the structure. The dead load of a component is computed by multiplying its volume by the density of the material. Because both the densities and the dimensions of the components are known with reasonable accuracy, dead loads in a building can be estimated with greater certainty than other load types. Densities of some of the commonly used materials are given in Tables 3.5 and 3.6 in Principles in Practice at the end of this chapter.

The dead load for which a building component is designed includes the self-load of the component plus the dead loads of all other components that it supports. For example, the dead load on a column includes the weight of the column itself plus all the dead load imposed on it. In Figure 3.3, the dead load on a column is the weight of the column plus the dead load from the beams and slab resting on it. Similarly, the dead load on a beam is the weight of the beam itself plus the dead load from the slab that it supports. The dead load on the slab is only the self-weight of the slab. However, if the slab supports a floor finish, ceiling, light fixtures, or plumbing and electrical pipes, their weights must be included in the dead load acting on the slab.

3.2 LIVE LOADS

While the dead load is a permanent load on the structure, *live load* is defined as the load whose magnitude and placement change with time. Such loads are due to the weights of people (animals, if the building houses animals), furniture, movable equipment, and stored materials. As shown in Figure 3.1, live loads are further divided into

- Floor live load
- Roof live load

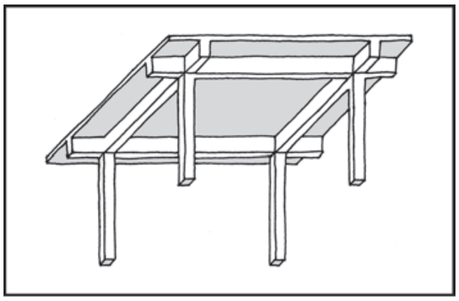


FIGURE 3.3 The dead load on the column of a building includes the weight of all components that it supports, such as the beams and floor slab plus the self load of the column.

NOTE

Loads in the SI System of Units

The unit of measurement for load in the SI system of units is newton, which is abbreviated N. A newton is even smaller than a pound (1lb = 4.45 N). Therefore, the unit kilonewton (kN) is commonly used.

For the load on a floor, the unit newton per square meter (N/m^2) is used instead of pound per square foot (psf). A newton per square meter is a pascal (Pa), and a kN/m^2 is a kilopascal (kPa). Thus, 1.0 N/m^2 is synonymous with 1.0 Pa, and 1.0 kN/m^2 with 1.0 kPa; 1 psf = 47.88 Pa.

For the load on a linear element, the unit newton per meter (N/m), or kilonewton per meter (kN/m) is used. The load on a column is expressed in newtons (N) or kilonewtons (kN).

(For conversion from the U.S. system of units to the SI system of units, and vice versa, see Appendix A.)

FLOOR LIVE LOAD

Floor live load depends on the occupancy and the use of the building. Therefore, it is also called the *occupancy load*, and it is different for different occupancies. For instance, the floor live load for a library stack room is higher than the floor live load for a library reading room, which in turn is higher than the floor live load for an apartment building.

Floor live loads are determined by aggregating the loads of all people, furniture, and movable equipment that may result from the particular occupancy. Safety considerations require that the worst expected situation be considered so that the structure is designed for the maximum possible live load that may be placed on it.

Based on a large number of surveys, floor live loads for various commonly encountered occupancies, such as individual dwellings, hotels, apartment buildings, libraries, office buildings, and industrial structures, have been determined and are contained in building code tables. Table 3.1 gives floor live loads for a few representative occupancies. For instance, the floor live load for a library stack room is 150 psf, for a library reading room is 60 psf, and for an apartment building is 40 psf. Note that these are the minimum floor live loads for which the building must be designed. Even if the actual live load on a floor is smaller, the building must be designed for the minimum live load specified by the building code.

The floor live load values in Table 3.1 are conservative. In most situations, the actual loads are smaller than those given. However, the architect or the engineer must recognize unusual situations that may lead to a greater actual load than the one specified in the code. In such situations, the higher anticipated load should be used.

Additionally, if the live load for an occupancy not included in building code tables is to be obtained, the architect or the structural engineer must determine it from first principles, taking into account all the loads that may be expected on the structure. Most building codes require that such live load values be approved by the building official. (At this stage, the reader is advised to study the examples given in Principles in Practice at the end of this chapter.)

ROOF LIVE LOAD

The live load on a roof takes into account the weight of repair personnel and temporary storage of construction or repair materials and equipment on the roof. Roof live load is generally given as 20 psf acting on the horizontal projected area of the roof, Figure 3.4.

TABLE 3.1 MINIMUM FLOOR LIVE LOADS FOR SELECTED OCCUPANCIES

Occupancy	Description	Load (psf)
Access floor system	Office use	50
	Computer use	100
Auditoriums	Fixed seating areas	60
	Movable seating areas	100
	Stage areas and enclosed platforms	125
Garages	Passenger cars	40
Hospitals	Wards and rooms	40
	Operating theaters	60
Libraries	Reading rooms	60
	Stack rooms	150
Manufacturing	Light	125
	Heavy	250
Offices	General office	50
	Corridors	80
	Lobbies	100
Residential dwellings	Dwellings and hotel guest rooms	40
	Habitable attics	30
	Corridors, public spaces, and balconies	100
Schools	Classrooms	40
	Corridors and lobbies	80
Stores	Light	125
	Heavy	250

Note: For authoritative information, refer to the building code of the jurisdiction.

This applies to a roof that will not be used in the future as a floor. If the building is expected to be extended vertically in the future, the roof live load is the floor live load for the anticipated future occupancy. Additionally, if the roof is to be landscaped, the load due to the growth medium and landscaping elements must be considered as dead load on the roof.

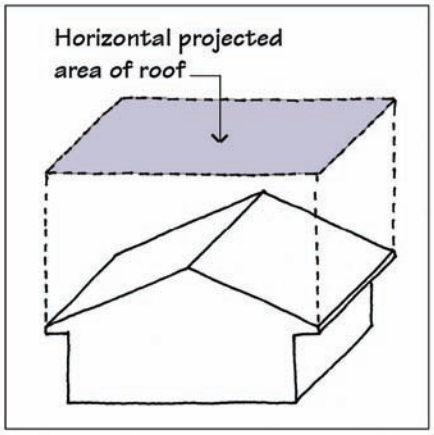


FIGURE 3.4 Horizontal projected area of a pitched roof.

3.3 RAIN LOAD

Although roofs are designed to have adequate drainage so that no accumulation of water occurs, loads resulting from accidental accumulation of melted snow or rainwater must be considered as a possibility. Drains may be blocked by windblown debris or hail aggregating on the roof or the formation of ice dams near the drains.

Long-span, relatively flat roofs are particularly vulnerable to rainwater accumulation because, being flexible, they deflect under the weight of water. This deflection leads to yet more accumulated water, causing additional deflection, which increases accumulation. If adequate stiffness is not provided in the roof, the progressive increase of deflection can cause excessive load on the roof. Water accumulation has been the cause of complete collapse of several long-span roofs.

Generally, roofs with slope greater than $\frac{1}{4}$ in. to 1 ft (1:48 or, say, 1:50 slope) are not subjected to accumulated rainwater unless roof drains are blocked. Building codes mandate $\frac{1}{4}$ in. to 1 ft as the minimum slope required for roofs, which, apart from providing positive drainage, also helps to increase the life and improve the performance of roof (waterproofing) membranes.

Building codes also require that in addition to primary drains, roofs must be provided with secondary (overflow) drains. The secondary drains must be at least 2 in. above the primary drains so that if the primary drainage system gets blocked, the secondary system will be able to drain the water off the roof, Figure 3.5.

Water accumulation generally occurs on roofs that are provided with a parapet. In the absence of a parapet, water accumulation will not occur generally. Therefore, secondary drains are not required on unparapeted roofs or on steep roofs.

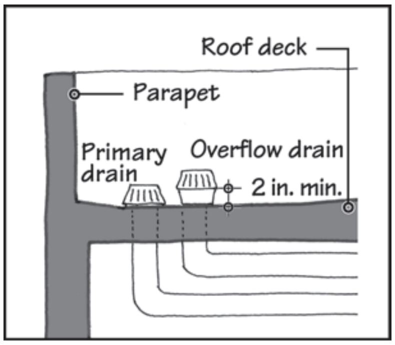


FIGURE 3.5 A roof with a parapet must be provided with two independent drainage systems.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The two main categories under which all building loads may be classified are
   - **a.** dead loads and live loads.
   - **b.** gravity loads and lateral loads.
   - **c.** terrestrial loads and celestial loads.
   - **d.** first-class and second-class loads.
2. The loads on a floor are generally expressed in
   - **a.** lb/ft^2.
   - **b.** lb/ft.
   - **c.** lb.
   - **d.** lb/ft^3.
   - **e.** none of the above.
3. The loads on a beam are generally expressed in
   - **a.** lb/ft^2.
   - **b.** lb/ft.
   - **c.** lb.
   - **d.** lb/ft^3.
   - **e.** none of the above.
4. The loads on a column are generally expressed in
   - **a.** lb/ft^2.
   - **b.** lb/ft.
   - **c.** lb.
   - **d.** lb/ft^3.
   - **e.** none of the above.
5. Which of the following loads can be estimated with greatest certainty?
   - **a.** Dead loads
   - **b.** Live loads
   - **c.** Wind loads
   - **d.** Earthquake loads
   - **e.** Snow loads
6. The floor live load in a residential occupancy is generally assumed to be
   - **a.** 40 psf.
   - **b.** 10 psf.
   - **c.** 20 psf.
   - **d.** 5 psf.
   - **e.** none of the above.
7. Which of the following occupancies has the highest floor live load?
   - **a.** Classrooms
   - **b.** Hotel guest rooms
   - **c.** Library stack rooms
   - **d.** Library reading rooms
   - **e.** Offices
8. The roof live load in a building is generally
   - **a.** less than the floor live load.
   - **b.** greater than the floor live load.
   - **c.** the same as the floor live load.
9. Roof live load is a function of the building's occupancy.
   - **a.** True
   - **b.** False
10. In which of the following roofs will you consider the effect of rain load?
    - **a.** Roof with a parapet
    - **b.** Roof without a parapet

3.4 WIND LOAD BASICS

Although wind loads are primarily horizontal, they also exert an upward force on horizontal elements such as flat and low-slope roofs. Resistance against upward wind force is provided by anchoring the building to its foundations. Resistance against horizontal loads requires anchorage to foundations and the use of stiffening elements. These stiffening elements are commonly referred to as *wind-bracing elements*.

The wind-bracing requirement for a building is precisely the same as the requirement for either diagonal bracing or sheet bracing of a bookshelf. If a book rack is constructed of several shelves mounted on two side supports, it will be adequate to carry the gravity load from the books, but the assembly will be unstable. When acted upon by a horizontal force from either direction, it will move sideways (or *rack*), as shown by the dotted lines in Figure 3.6(a).

Racking of the bookshelf can be prevented by diagonally bracing one of its faces, Figure 3.6(b). An alternative method of stiffening the book rack is to apply a sheet material over the entire face instead of diagonal braces. Sheet bracing generally provides greater lateral stiffening than diagonal bracing.

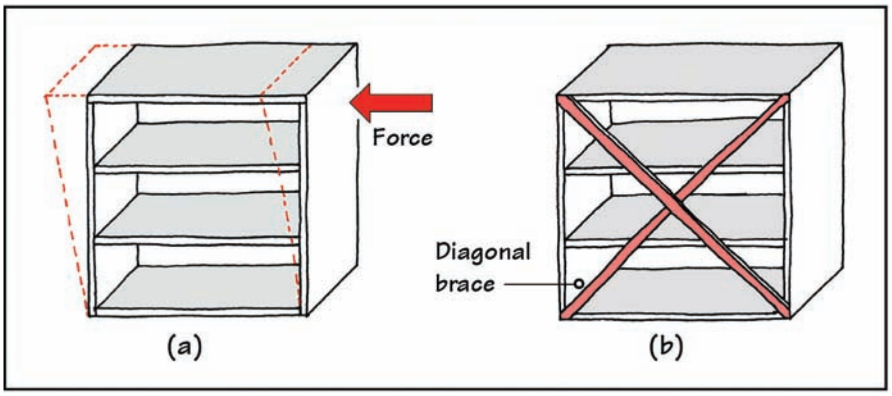


FIGURE 3.6 **(a)** When pushed by a horizontal force, a book rack constructed of several horizontal shelves and two vertical supports will move sideways (i.e., "rack"), as shown by the dashed lines. **(b)** The racking of shelves can be prevented by diagonal braces (as shown) or by sheet bracing.

For buildings, several methods of wind bracing are used, depending on the functional and aesthetic constraints of the building and the magnitude of wind loads. Because wind loads increase with the height of a building, stiffening the building against wind loads becomes increasingly important as the height of the building increases. In fact, the design of tall buildings is heavily dominated by wind-bracing requirements. Architects have often used this structural requirement as a forceful aesthetic expression of building facades in several buildings. Two such examples are shown in Figures 3.7 and 3.8.

As we will see in Sections 3.8 and 3.9, there is much similarity between the effects of wind load and earthquake load on buildings. Therefore, many of the structural strategies used for wind load resistance are also used for resisting earthquake loads. Thus, the more commonly used term for wind bracing is *lateral bracing* because both wind load and earthquake load represent lateral loads on buildings.

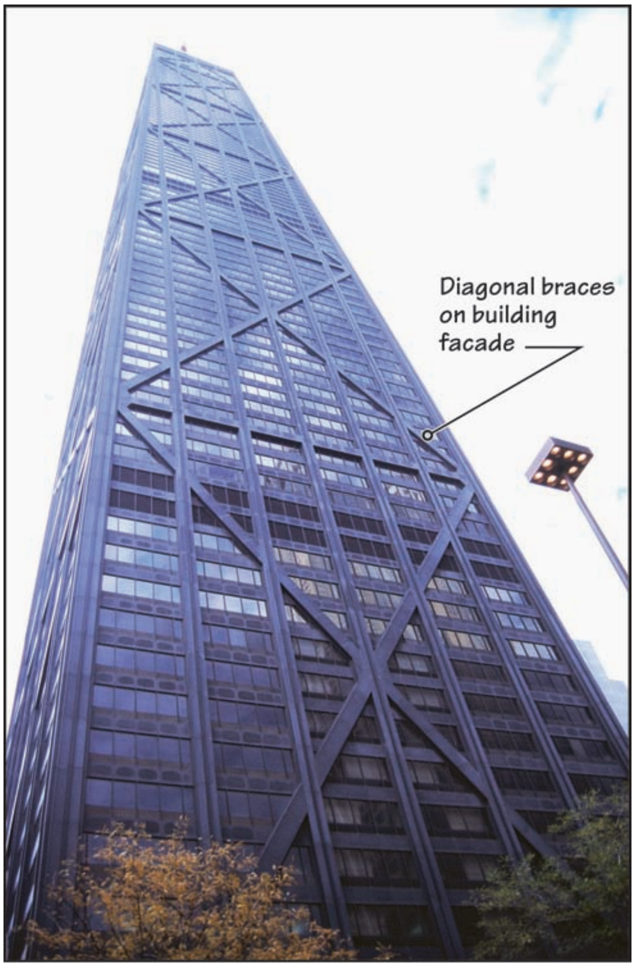


FIGURE 3.7 The lateral load resistance in the 100-story John Hancock Center, Chicago, has been provided by diagonal braces on its exterior facade.

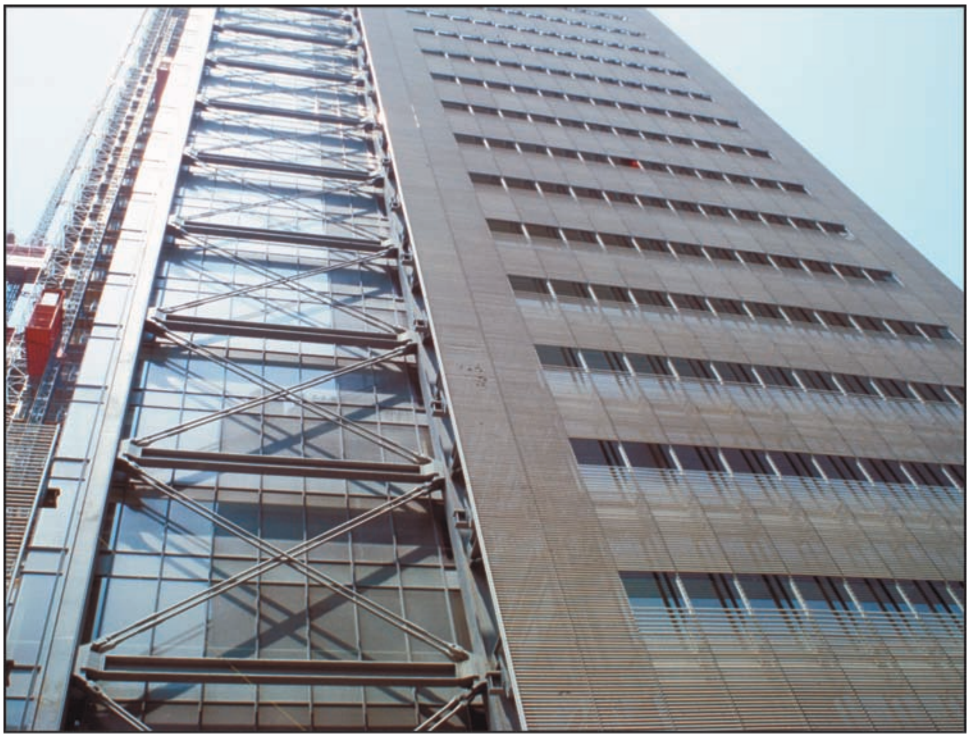


FIGURE 3.8 Diagonal braces used on the exterior facade of the 52-story New York Times Building, New York City, provide lateral load resistance. The building was designed by Renzo Piano Building Workshop in collaboration with Fox and Fowle Architects and was completed in 2007. In both the John Hancock Center and the New York Times Building, the lateral load resistance has been provided by diagonal braces on the building's exterior—a structural feature that makes a bold architectural statement. However, diagonal braces may also be used in the building's interior. Additionally, several other means of wind and earthquake load resistance are available and are described in the Principles and Practice section of Chapter 19.

TORNADOES, HURRICANES, AND STRAIGHT-LINE WINDSTORMS

The wind speed is fundamental to determining wind loads on buildings. It is the most important factor, because the wind load is directly proportional to the square of wind speed. In other words, if other factors that affect wind loads are ignored, doubling the wind speed quadruples the wind load. Tripling the wind speed makes wind load nine times larger.

Obviously, buildings must be designed for the maximum probable wind speed at that location. The highest wind speeds are usually contained in a tornado—a rotating funnel-shaped column of air that produces strong suction, Figure 3.9.

Because of the extremely small probability that a violent tornado will hit a particular building, design wind speeds adopted by building codes for various locations do not reflect the

FIGURE 3.9 Tornado in Seymour, Texas, on April 10, 1979.
(Photo obtained from OAR/ERL/National Severe Storms Laboratory (NSSL)/NOAA)

NOTE

A Note on Tornadoes

The suction produced in a tornado funnel lifts objects into the air like a giant suction pump. If a tornado hits a water body such as a lake or a sea, a waterspout is formed. Nearly 60% of all tornadoes are weak in intensity. However, 38% are strong enough to topple walls and blow roofs off buildings. Nearly 2% of tornadoes are so violent that they destroy virtually everything in their path.

Actual measurements of wind speeds in a tornado are not available because the area of ground struck by a tornado is relatively small. Post-tornado damage observations have revealed that an average tornado has a life span of nearly 30 min and covers a nearly 10-mi-long by 0.25-mi-wide area of ground, that is, 2.5 mi^2.

Thus, the probability of a tornado hitting a particular building or intercepting a permanently located wind speed-measuring instrument, such as that installed at an airport, is very small. Additionally, the destructive power of a tornado is so large that whenever a tornado has hit such measuring instruments, it has completely destroyed them.

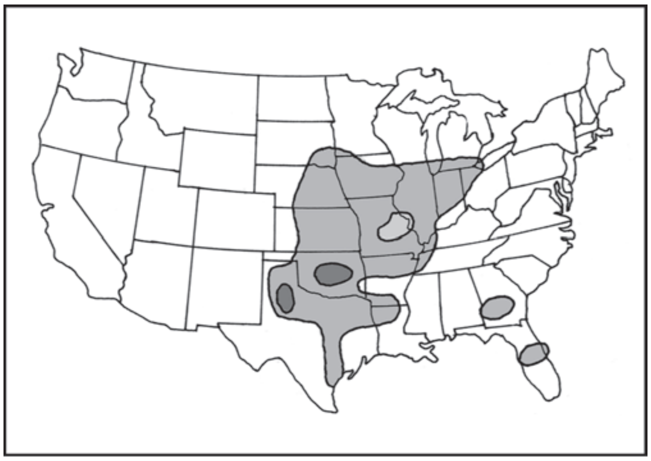


FIGURE 3.10 An approximate representation of tornado-prone regions of the United States. The darker the color of the region, the greater the tornado activity. However, no region of the United States is absolutely tornado-free. For hurricane-prone regions of the United States, see Figure 3.11.

wind speeds obtained in tornadoes. In spite of the fact that design wind speeds do not account for tornadoes, buildings have to be designed to resist tornadoes in tornado-prone locations. For this purpose, sufficient empirical information is available to design and construct tornado-resistant buildings. Figure 3.10 shows tornado-prone areas in the United States.

After tornadoes, hurricanes represent the next most severe wind phenomenon. Known as *typhoons* or *tropical cyclones* in Asia, hurricanes pose greater life safety and economic hazards to buildings and urban infrastructure than tornadoes. Like a tornado, a hurricane is a rotating funnel-shaped wind storm, except that the funnel in a hurricane is much larger than that of a tornado.

An average hurricane within which strong winds exist has a diameter of about 500 mi and has an average lifespan of 10 days. Depending on the location, winds of up to 180 mph may occur within a hurricane. Most damage from hurricanes occurs in coastal areas and is caused primarily by the uplifting of roofs, windborne debris, and uprooted trees or branches of trees. Tidal surges caused by hurricanes can be more devastating than wind-created damage.

As a hurricane travels inland, it loses energy and degenerates into a tropical rain storm. In the United States, hurricanes develop over warm areas in the Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and northeastern Pacific Ocean. Although hurricane-induced property damage has increased over the years in the United States due to the migration of population toward coastal areas, loss of life has decreased due to improvements in forecasting and warning systems.

After tornadoes and hurricanes, local windstorms (e.g., thunderstorms) are the next category of violent wind activity. Because they are nonrotating or nonspinning, they are also referred to as *straight-line winds*. Being a local phenomenon, a windstorm strikes a much smaller area of ground than a hurricane. However, the frequency of occurrence of windstorms is much higher. Consequently, the damage caused by windstorms is substantial. In determining the design wind speed for a location, we consider both the hurricane activity and the straight-line wind activity.

DESIGN (BASIC) WIND SPEED

Wind tends to be gusty, implying that the wind speed varies continuously. Because wind speed–measuring instrumentation has a finite response period over which it averages the wind speed, instantaneous wind speed measurements are not possible. The shortest averaging interval used in wind speed–measuring instruments in the United States is 3 seconds. Because building design must be based on maximum wind speeds, we refer to the maximum wind speed as *peak 3-s gust speed*.

Peak 3-s gust speeds for several selected locations are continuously recorded in the United States. The peak 3-s gust speed that is not likely to be exceeded for 700 years at a location is defined as the *basic wind speed* for that location. Basic wind speed, also called *design wind speed*, is used in determining the design wind loads on buildings.

The period of 700 years is called the *return period*. This return period is used for determining the design wind speed for designing buildings with an average risk occupancy, such as individual homes, hotels, and apartment buildings. A longer return period (1,700 years) is used for determining the design wind speed for occupancies of above-average risk, such as emergency shelters, broadcasting stations, and police stations. A shorter return period (300 years) is used for below-average risk occupancies, such as farm buildings for animal shelters. These return periods may seem excessive, but they include a statistically determined safety margin.

By international agreement, wind speeds are recorded at a height of 33 ft (10 m) above ground. Although there are several other recording stations, wind speeds are typically recorded at local airports. A wind speed map giving design wind speed values (with a 700-year return period) for the United States is shown in Figure 3.11. Map values are to be used as a general guide. Local building codes must be referenced for precise values.

INDUCED PRESSURE AND SUCTION

Being a fluid, wind exerts pressure on building surfaces. The direction of wind pressure is always perpendicular to the building surface. Thus, on a flat roof, wind pressure is vertical.

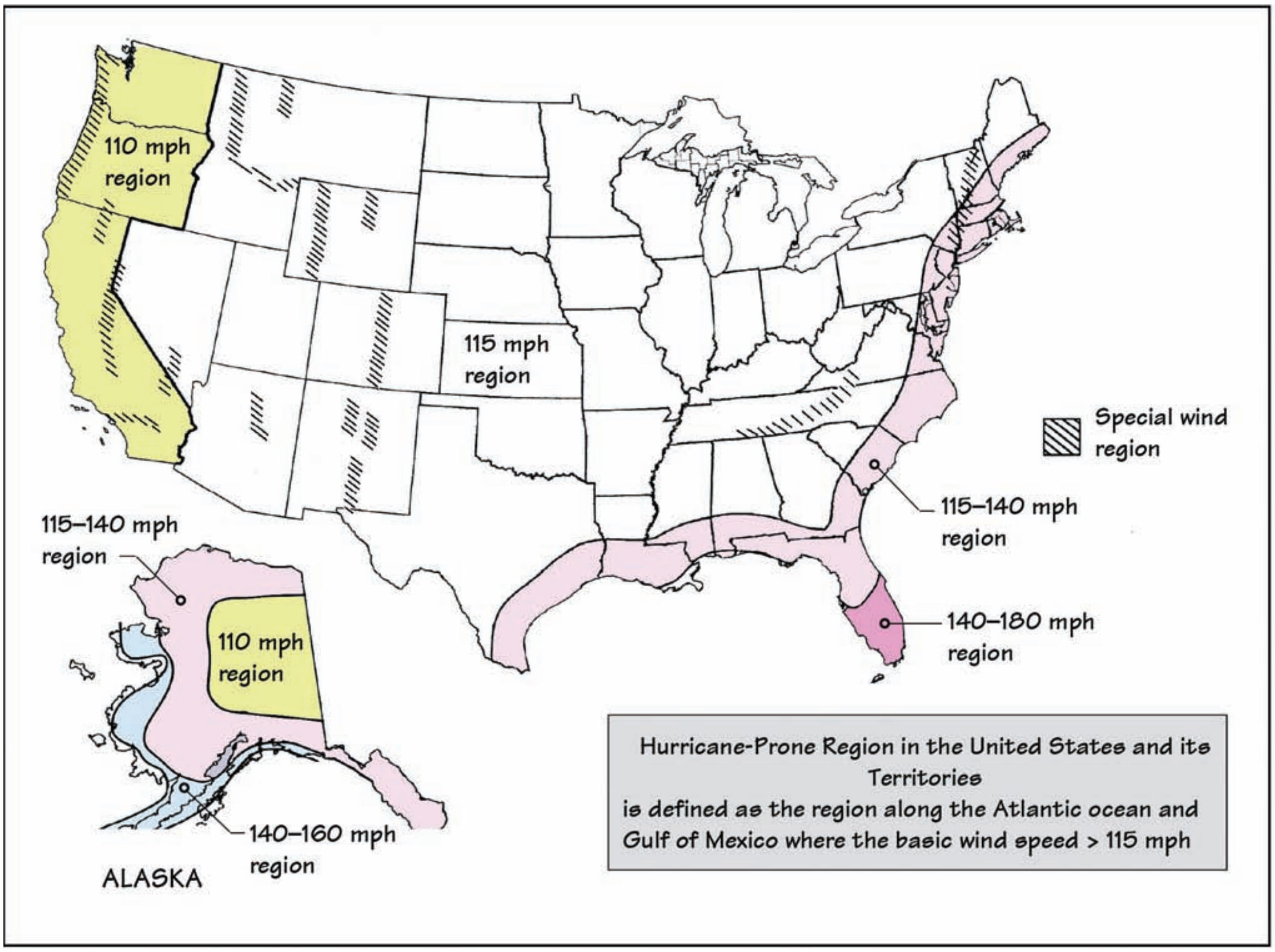

110 mph region
115 mph region
Special wind region
115–140 mph region
140–180 mph region
115–140 mph region
110 mph region
140–160 mph region
ALASKA
Hurricane-Prone Region in the United States and its Territories
is defined as the region along the Atlantic ocean and Gulf of Mexico where the basic wind speed > 115 mph

FIGURE 3.11 Three-second peak gust wind speed (basic wind speed) map of the continental United States and Alaska in miles per hour (mph) for the design of buildings with average risk (return period of 700 years), such as homes, offices, restaurants, and so on.
Source: From the American Society of Civil Engineers, Minimum Design Loads for Buildings and Other Structures, SEI/ASCE 7-10 (2010), by American Society of Civil Engineers.

On a vertical wall, it is horizontal. Whatever the direction of pressure, it acts either toward the surface or away from the surface (suction).

On a rectangular building, wind causes inward force on the windward wall and suction on the other walls (leeward wall and side walls), Figure 3.12(a). The largest pressures occur on the windward and leeward walls. Because a given wall may be a windward or a leeward wall, depending on wind direction, it has to be designed for both the maximum (inward) pressure and maximum suction.

Wind tunnel tests have shown that on the windward wall, wind pressure varies with height, increasing as the height increases. On the leeward wall, there is no appreciable change in pressure with respect to height. Hence, uniform pressure is assumed to act on the leeward wall, Figure 3.12(b).

As for a roof, a flat or near-flat roof is subjected to suction. A pitched roof has to be designed for suction as well as downward pressure. This is because if the wind blows parallel to the ridge, the roof is under suction, Figure 3.13(a). If the wind blows perpendicular to the ridge, the leeward slope is subjected to suction. The windward slope of the roof, however, comes under suction if the roof slope is small, which turns to downward (toward the roof) pressure as the slope increases, Figure 3.13(b).

SPATIAL VARIATION OF WIND PRESSURE

Wind pressure on a building's facade not only varies with height above ground, but it also varies from point to point at the same height above ground. For example, significantly larger pressures are obtained at the edges and corners of a building facade than in the central part (field). In other words, a corner window is subjected to greater pressure than a window in the middle of the wall. Similarly, wind pressures on the corners of a roof are greater than those along the perimeter of the roof, which in turn are greater than those in the middle of the roof.

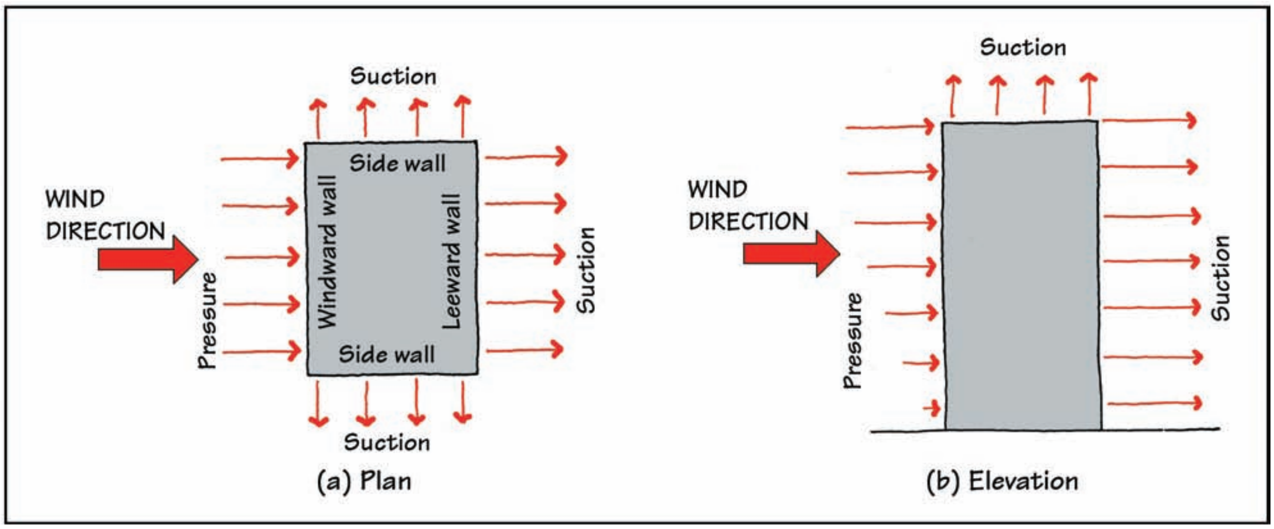

Suction
Side wall
WIND DIRECTION
Pressure
Windward wall
Leeward wall
Suction
Side wall
Suction
(a) Plan
Suction
WIND DIRECTION
Pressure
Suction
(b) Elevation

FIGURE 3.12 Wind pressures exerted on the walls of a rectilinear building: **(a)** in plan and **(b)** in elevation. Note that on the windward wall, wind pressure increases with height. On the leeward wall, the pressure is constant over the entire height of the wall.

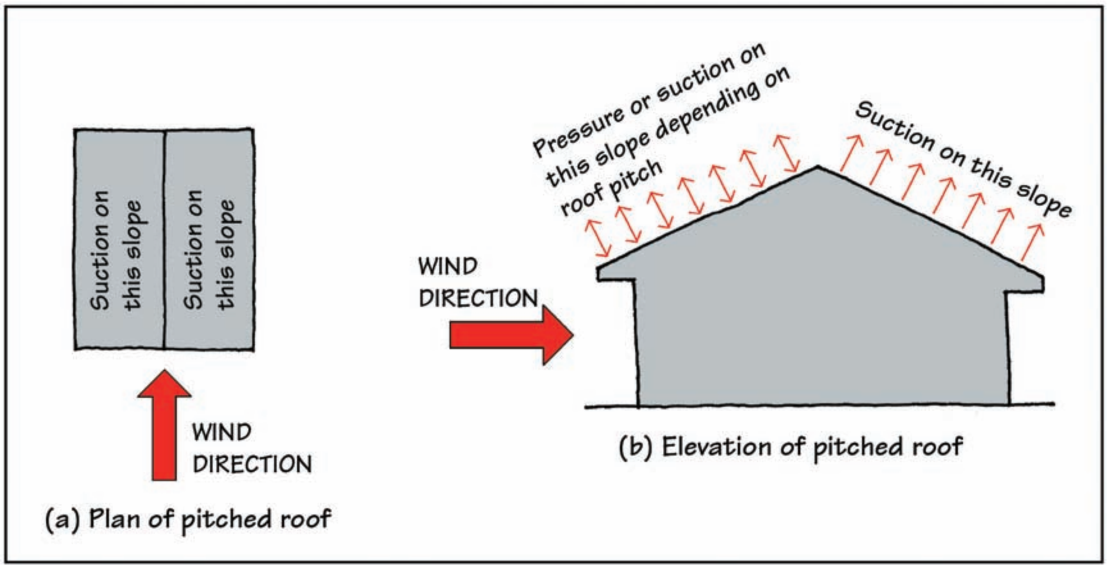

Suction on this slope
Suction on this slope
WIND DIRECTION
(a) Plan of pitched roof
Pressure or suction on this slope depending on roof pitch
Suction on this slope
WIND DIRECTION
(b) Elevation of pitched roof

FIGURE 3.13 Wind pressures on a pitched roof.

3.5 FACTORS THAT AFFECT WIND LOADS

The predominant effect of wind speed on wind pressure has already been mentioned. Other important factors that affect wind pressure are:

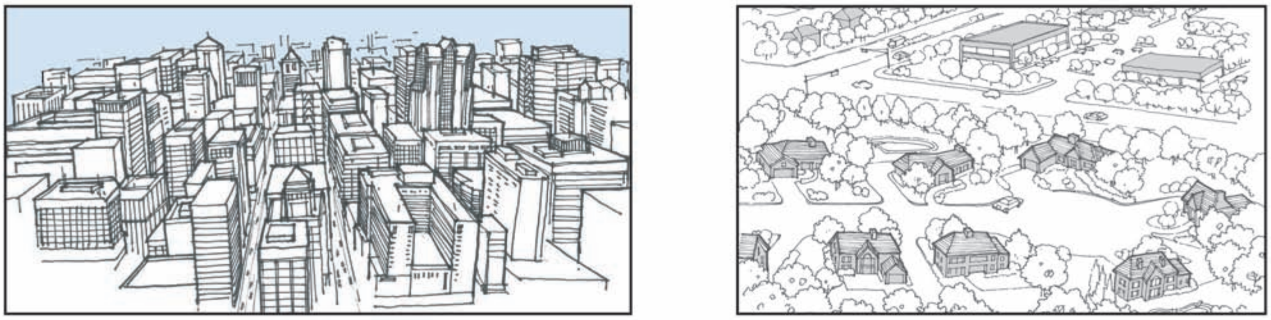
- Height above ground
- Exposure classification of the site
- Enclosure classification of the building

HEIGHT ABOVE GROUND

Through our daily experience, we know that wind speed increases with height above the ground. An open window on a higher floor of a multistory building feels breezier than one on a lower floor. Consequently, wind pressures are higher on a tall building than on a short one.

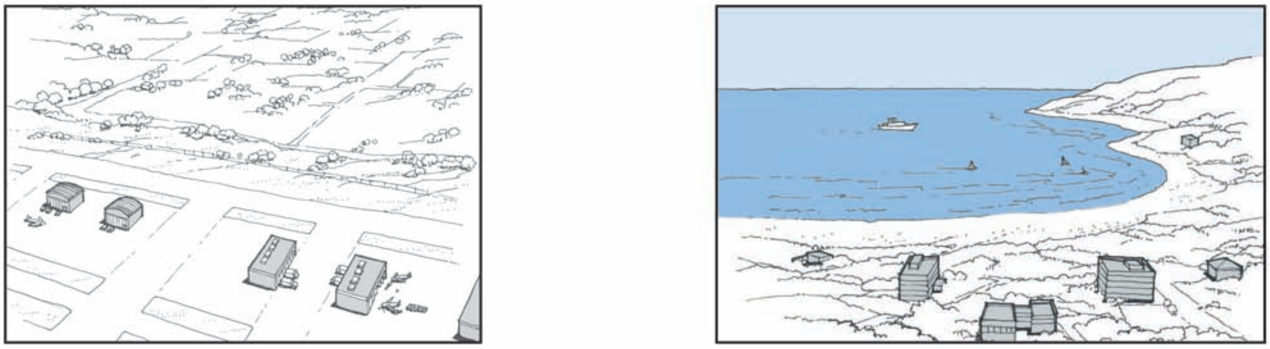
EXPOSURE CLASSIFICATION OF THE SITE

Wind pressures on a building also depend on the neighborhood in which the building is located. A building located in a vast open stretch of land, with no other buildings or obstructions in its neighborhood, is subjected to greater wind pressures than the same building located in a densely built-up area. This is because the wind speed in an open stretch of land is higher than in a built-up or highly wooded area.



EXPOSURE B—A downtown location

EXPOSURE B—An urban or suburban location



EXPOSURE C—An open country or grassland.
Wind speed measurements are made in Exposure C.

EXPOSURE D—A flat, unobstructed site facing a large water body

FIGURE 3.14 Site exposure categories—B, C, and D. A densely built downtown location was earlier categorized as Exposure Category A, but it was discovered that, due to the tunneling effect, wind pressures in some parts of a downtown area are equal to those of an urban/suburban location (Exposure Category B). Therefore, Category A was deleted.

Building sites are classified into three types, based on the roughness of the ground. The roughness of the ground is referred to as the *exposure category* of the site. The three exposure categories to which a particular site may belong are B, C, or D. *Exposure Category B*, or simply *Exposure B*, refers to an urban, suburban, or wooded area with several closely spaced obstructions, Figure 3.14. A large city center with several high-rise and closely spaced buildings also belongs to Exposure B.

Exposure C refers to open terrain with scattered obstructions involving heights generally less than 30 ft. An airport is a typical example of Exposure C. *Exposure D* refers to flat, unobstructed ground facing a large body of water (a large lake- or seafront). Everything else being the same, wind pressures are highest in Exposure D, followed by Exposure C, and least in Exposure B.

ENCLOSURE CLASSIFICATION OF THE BUILDING

Building envelopes are not perfectly airtight. They are subject to air infiltration and exfiltration. Additionally, they have windows and doors, which may not be fully sealed. Because of air infiltration through the openings, the interior of a building is always subjected to some internal pressure in addition to the pressure on the exterior envelope of the building.

Internal pressure is particularly critical in buildings that have large openings on one side or two adjacent sides, because these tend to "cup" the wind, creating a "ballooning" effect, Figure 3.15. Buildings in which the ballooning effect is large are called *partially enclosed buildings*. They include buildings in which the area of openings in one wall is much greater than that in the remaining walls, such as aircraft hangars, warehouses with open dock doors, or garages that are open only on one side.

A building that is not partially enclosed is called an *enclosed building*. Most buildings belong to this (enclosed building) category. Everything else being the same, a partially enclosed building is subjected to greater wind pressure than an enclosed building. If the exterior doors and windows in a building shatter in a windstorm, an enclosed building may become a partially enclosed building, increasing the wind pressure on the building for which it has not been designed. Therefore, the design of the building must ensure that its envelope remains

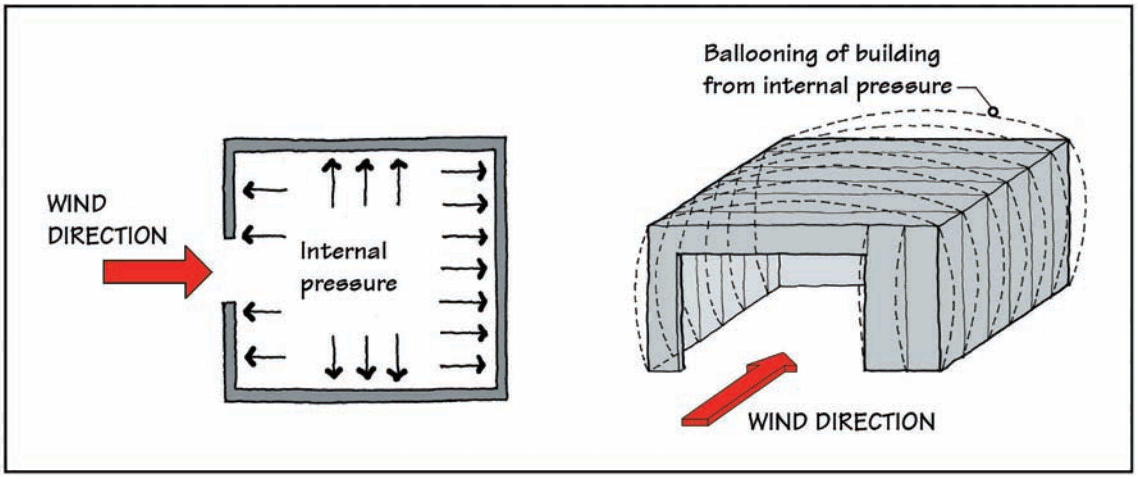


FIGURE 3.15 Ballooning of a building with a relatively large opening in one wall. Such a building is referred to as a *partially enclosed building*. A building that is not partially enclosed is called an *enclosed building*. Most buildings belong to the enclosed building category.

EXPAND YOUR KNOWLEDGE

Important Facts About Wind Loads

1. Wind Load Is Expressed in Terms of Wind Pressure
Wind loads on buildings are generally expressed as wind pressure, that is, in pounds per square foot (psf).

2. Wind Pressure Is Proportional to the Square of Wind Speed
Everything else being the same, the wind pressure on a building component is proportional to the square of wind speed. More precisely:

$$p = \left[\frac{V}{20}\right]^2$$

where: p = wind pressure in pounds per square foot (psf)
V = wind speed in miles per hour (mph)

Thus, if $V = 100$ mph, $p = 25$ psf. If $V = 90$ mph, $p = 20$ psf. For $V = 10$ mph, $p = 0.25$ psf.

3. Magnitude of Wind Pressures on Low-Rise Buildings
Because wind speed refers to that measured at a height of 33 ft (10 m) above ground, the approximate value of wind pressure on the components of most low-rise buildings (one to three stories tall) can be obtained by the simplified equation just given. This is an extremely important result, as it helps us understand the performance of air and vapor barriers, covered in Chapter 6.

4. Wind Pressure on a Building Component Equals the Difference Between Inside and Outside Air Pressures
The wind pressure on a building component, such as a wall, window, or roof is, in fact, the difference between inside and outside air pressures. If the component is subjected to suction under wind loads, it implies that the inside pressure is greater than the outside pressure. Conversely, if the outside pressure is greater than the inside pressure, the component will be subjected to push-in pressure. The inside pressure in a building is generally the atmospheric pressure. The outside pressure changes with wind speed.

intact under the worst expected windstorm. Many buildings have suddenly collapsed (or suffered major damage) under a storm immediately after the collapse of one or more of their exterior doors or windows (see Figure 3.25).

3.6 ROOF SNOW LOAD

A roof is designed for either the roof live load or the snow load, whichever is greater. The reason is that in the event of full snow load on a roof, the roof is not likely to be accessed by a repair or construction crew, who would impose additional live load on it. Like the roof live load, snow load is also expressed in terms of the horizontal projected area of the roof (Figure 3.4).

Fundamental to determining roof snow load is the ground snow load of a location. Ground snow load values with a 50-year return period for selected U.S. locations are given in Table 3.2. These values should be treated as approximate. For authoritative data, the building code or the city's building department should be consulted.

FACTORS THAT AFFECT ROOF SNOW LOAD

The factors that affect snow load on a roof are:

- *Ground snow load at the location*
- *Roof slope* The greater the slope of the roof, the smaller the snow load. For a flat or near-flat roof, the snow load should theoretically be equal to the ground snow load.

TABLE 3.2 APPROXIMATE GROUND SNOW LOADS FOR SELECTED LOCATIONS

Location	Snow load psf	Location	Snow load psf
Phoenix, Arizona	5	Jackson, Mississippi	5
Little Rock, Arkansas	10	Albany, New York	35
Atlanta, Georgia	10	Raleigh, North Carolina	15
Springfield, Illinois	20	Harrisburg, Pennsylvania	25
Des Moines, Iowa	25	Dallas, Texas	10
Topeka, Kansas	25	Anchorage, Alaska	50

Note: The snow load information given is approximate and has been adapted from the American Society of Civil Engineers, Minimum Design Loads for Buildings and Other Structures , SEI/ASCE 7-10 (2010), by American Society of Civil Engineers.

However, records of measurements of snow deposits on roofs have shown that less snow is typically present on flat roofs than on the ground because wind blows the snow off the roofs and some snow melts due to heat escaping from the heated interiors. Snow load on flat roofs in open areas (i.e., areas that are not obstructed by wind-shielding elements such as higher structures, terrain, and trees) can be as low as 60% of that on the nearby ground.

- *Wind exposure classification of the site (Exposure B, C, or D)* Everything else being the same, Exposure D has the lowest snow load, due to the high wind speeds, and Exposure B has the highest snow load.
- *Warm roof or cold roof* An example of a warm roof is that of a continuously heated greenhouse, and an example of a cold roof is that of a typical residential structure in which the attic space is ventilated, which keeps the roof cold. An unheated building is another example of a structure with a cold roof. Snow load is smaller on a warm roof than on a cold roof.
- *Risk category of building's occupancy* This factor is essentially the same as for the wind loads. Above-average risk occupancies, such as emergency shelters, police stations, fire stations, and radio and television studios, are designed for greater snow load than average-risk occupancies.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

11. Highest wind speeds are usually obtained in
a. hurricanes.
b. wind storms.
c. thunderstorms.
d. tornadoes.

12. An average tornado strikes a larger area on the ground than a hurricane.
a. True
b. False

13. The design wind speed is also referred to as the
a. standard wind speed.
b. official wind speed.
c. uniform wind speed.
d. straight-line wind speed.
e. basic wind speed.

14. The design wind speed for an average-risk building at a location has a probability of occurrence of
a. once in 300 years.
b. once in 200 years.
c. once in 100 years.
d. once in 50 years.
e. none of the above.

15. The design wind speed for a location is the peak
a. 60-s gust speed.
b. 10-s gust speed.
c. 5-s gust speed.
d. 3-s gust speed.
e. 1-s gust speed.

16. For most of the United States, the design wind speed for an average-risk building is
a. 95 mph.
b. 105 mph.
c. 115 mph.
d. 125 mph.
e. 150 mph.

17. For wind blowing along one of the two major axes of a rectangular building, the windward wall is subjected to positive (toward-the-wall) pressure.
a. True
b. False

18. For wind blowing along one of the two major axes of a rectangular building, the leeward wall is subjected to positive (toward-the-wall) pressure.
a. True
b. False

19. For wind blowing along one of the two major axes of a rectangular building, the side walls are subjected to positive (toward-the-wall) pressure.
a. True
b. False

20. On a leeward wall, the wind pressure
a. increases with height above the ground.
b. decreases with height above the ground.
c. is almost constant with height above the ground.

21. With respect to wind pressure, a building site is classified in terms of
a. Exposures A, B, C, and D.
b. Exposures A, B, and C.
c. Exposures X, Y, and Z.
d. Exposures P, Q, R, and S.
e. Exposures B, C, and D.

22. The design snow load on a roof is a function of
a. ground snow load of the location.
b. roof slope.
c. wind exposure classification of the site.
d. all of the above.
e. both (a) and (b).

3.7 EARTHQUAKE LOAD

A severe earthquake is one of the most terrifying natural events a person can experience. Regardless of where it occurs, it makes instant headlines all over the world. In the past, earthquakes killed a large number of people. Today, earthquakes pose a smaller threat to life than in the past (at least in developed nations, and discounting the December 2004 tsunami in the Indian Ocean and the January 2010 Haiti earthquake) because of our improved knowledge of constructing earthquake-resistant structures. Statistics indicate that the current annual loss of life resulting from earthquakes is much smaller than that due to hurricanes, building fires, floods, or automobile accidents.

Ground shaking, the phenomenon most commonly associated with earthquakes, causes damage to buildings and other infrastructural facilities, Figure 3.16. Records show that the earthquakes of 1811 and 1812 in Missouri shifted the course of the Mississippi River considerably [Ref. 3.1]. In addition to ground shaking, a major earthquake can produce several related problems, such as landslides, surface fractures (Figure 3.17), soil liquefaction (Section 11.3), tsunamis, and fires.

TSUNAMIS

A tsunami is caused by the physical displacement of the seabed during an earthquake, which creates waves of up to 50 ft in height. So far, most tsunamis have occurred in the Pacific Ocean, with Japan witnessing the largest number of them—hence their Japanese name. However, the 2004 tsunami that occurred in the Indian Ocean was the most devastating in terms of the loss of human lives.

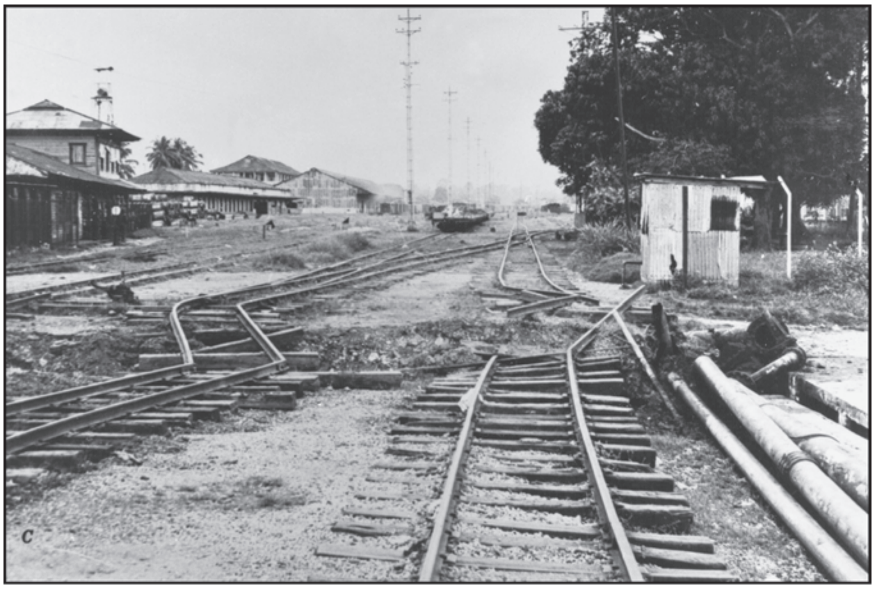


FIGURE 3.16 Damage to railroad tracks on the Puerto Barrios wharf caused by the 1976 Guatemala earthquake.
(Photo obtained from USGS, U.S. Geological Survey Library.)

GEOLOGICAL EXPLANATION OF EARTHQUAKES

The cause of earthquakes is fairly well established. However, we are still far from perfecting a methodology to accurately predict the location and time of earthquake occurrence.

Geologists believe that the earth's crust is divided into several individual segments called *crustal* or *tectonic plates*, Figure 3.18. These solid plates, floating on a molten mantle below, are constantly in motion relative to each other. The motion is so slow that it is significant only in geological time. The relative motion in the earth's crust causes compressive, tensile, or shear forces to develop, depending on whether the plates press against each other, pull apart, or slip laterally under one another. When these stresses exceed the maximum capacity of the crust to absorb them, a fracture at the crust occurs. It is this fracturing, or slippage, which is always sudden, that produces a shock wave known as *seismic motion*.

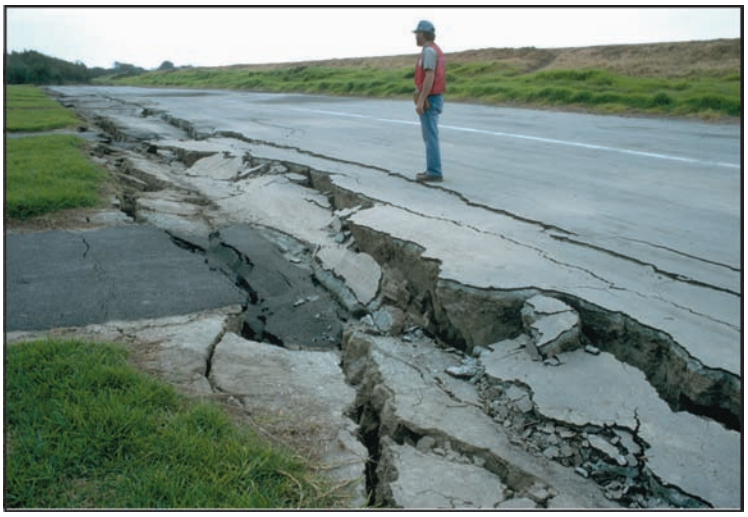


FIGURE 3.17 Fissures in the ground caused by the 1989 Loma Prieta earthquake, San Francisco Bay area (Richter magnitude 7.0).
(Photo obtained from USGS, U.S. Geological Survey Library.)

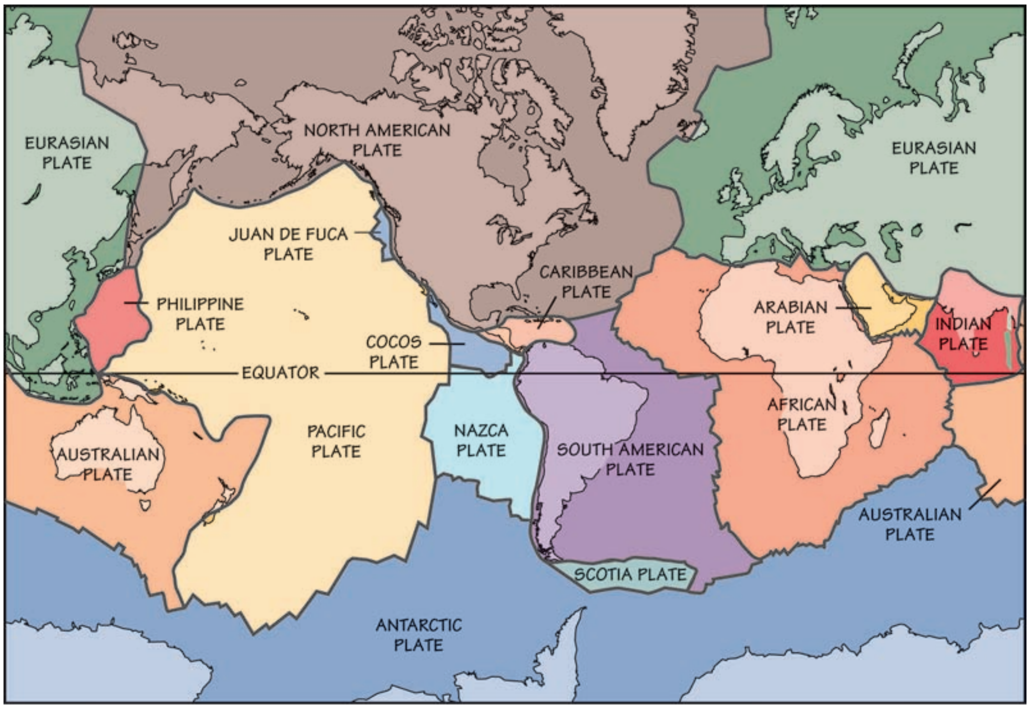

EURASIAN PLATE
NORTH AMERICAN PLATE
EURASIAN PLATE
JUAN DE FUCA PLATE
CARIBBEAN PLATE
PHILIPPINE PLATE
ARABIAN PLATE
INDIAN PLATE
COCOS PLATE
EQUATOR
AFRICAN PLATE
PACIFIC PLATE
NAZCA PLATE
AUSTRALIAN PLATE
SOUTH AMERICAN PLATE
AUSTRALIAN PLATE
SCOTIA PLATE
ANTARCTIC PLATE

FIGURE 3.18 Map of the earth with an approximate depiction of major tectonic plates. (Courtesy of the United States Geological Survey.)

The plane where the fracture occurs is called a *fault*. The location where the fault originates is called the *focus,* which is generally inside the earth's crust. The point directly above the focus on the earth's surface is called the *epicenter*, Figure 3.19.

The fracture on the surface of the earth may or may not be noticeable or may appear as a minor fissure, as shown in Figure 3.17. The 1906 San Francisco (California) earthquake left a deep ground rupture extending hundreds of miles. Known as the *San Andreas Fault*, it stands as a distinct landmark created by an earthquake.

FREQUENCY OF OCCURRENCE AND LOCATION OF EARTHQUAKES

An earthquake may occur at any location. In fact, mild earthquakes occur quite frequently: Several thousand a day occur in various regions of the earth, Table 3.3. They go unnoticed because they may occur in remote places or with a magnitude that is below the threshold of human perception.

The regions of the earth in proximity to plate boundaries are susceptible to more frequent and more severe earthquakes. Nearly 90% of all earthquakes occur in the vicinity of plate boundaries, because the plate boundaries represent lines of greater weakness in the earth's crust. Observe in Figure 3.18 that the Pacific plate and the North American plate meet along the West Coast of the United States—a region known for its high seismic activity.

The remaining 10% of earthquakes occur because of the faults within the plates. Called *intraplate earthquakes*, they occur far away from the plate boundaries. Earthquakes that have

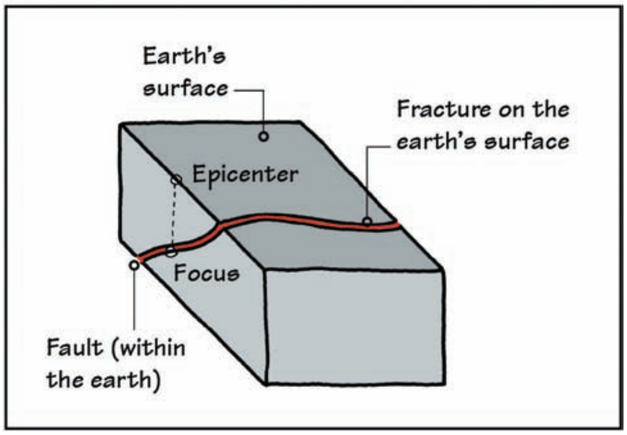

Earth's surface
Fracture on the earth's surface
Epicenter
Focus
Fault (within the earth)

FIGURE 3.19 Fault, focus, and epicenter of an earthquake.

TABLE 3.3 WORLDWIDE FREQUENCY OF EARTHQUAKE OCCURRENCE

Descriptor	Richter magnitude	Average frequency per year
Great	≥ 8.0	0–1
Major	7–7.9	17
Strong	6–6.9	134
Moderate	5–5.9	1,319
Light	4–4.9	13,000
Minor	3–3.9	130,000
Very minor	2–2.9	1,300,000

Source: From EQ Facts and Lists, National Earthquake Information Center, U.S., by USGS, U.S. Geological Survey Library.

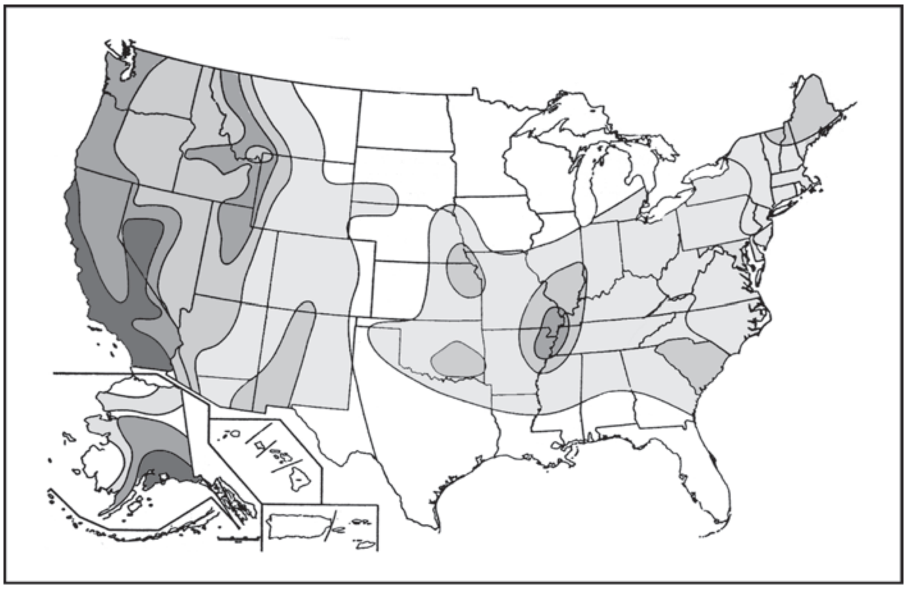


FIGURE 3.20 Map of the United States showing approximate variation of seismic activity. The darker the area, the greater the seismic activity. White areas have little or no seismic activity.

occurred in the Eastern and Midwestern United States are intraplate earthquakes. Intraplate earthquakes are infrequent but may be as severe as plate boundary earthquakes.

Because seismicity is a geographical activity, it is possible to delineate areas that are seismically more active than others. For the United States, this activity is shown in Figure 3.20, in which the degree of seismic activity is denoted by the darkness of the gray color. Thus, unshaded areas of the country have little or no seismic activity, and the darkest areas are seismically most active.

EARTHQUAKE INTENSITY—RICHTER MAGNITUDE

For the general public, the scale most commonly used to describe the intensity of an earthquake is the Richter scale. The Richter scale was devised in 1935 by Professor Charles Richter of the California Institute of Technology. The scale begins at zero but has no upper limit. However, the severest earthquake recorded to date on this scale is 9.0.

According to the Richter scale, the total energy released by an earthquake (E) is proportional to the Richter magnitude (R), as given by the following expression:

$$E \propto 10^{1.5R}$$

The symbol $\propto$ is the sign of proportionality, implying that earthquake energy is proportional to $10^{1.5R}$. Because $10^{1.5}$ is approximately equal to 32, this expression implies that an increase of 1.0 on the Richter scale gives a 32 times increase in the energy output of the earthquake. Thus, an earthquake measuring 8.0 on the Richter scale is nearly 32-fold more powerful than one measuring 7.0 and nearly 1,000 times more powerful than one measuring 6.0. (Note: $32 \times 32 =$ approximately 1,000.)

An earthquake of up to 2.0 on the Richter scale goes unnoticed by humans; 4.0 to 5.0 may cause slight damage to poorly designed buildings. At 7.0, the damage is usually extensive in poorly designed buildings. An earthquake with a magnitude of 6.5 and above is considered significant. Table 3.4 lists some of the major earthquakes that have occurred in various parts of the world in the past 100 years. (Major earthquakes may be measured by their Richter magnitude, number of fatalities, or loss of property.)

TABLE 3.4 SOME OF THE MAJOR EARTHQUAKES SINCE 1900

Year	Location	Richter magnitude	Loss of life
1905	Kangra, India	8.6	19,000
1906	Columbia and Ecuador	8.9	1,000
1906	San Francisco, USA	8.3	700
1906	South Central Chile	8.6	1,500
1907	Karatag, Tajikistan	8.0	12,000
1908	Messina, Italy	7.2	100,000
1920	Gansu, China	7.8	200,000
1923	Kanto, Japan	7.9	143,000
1927	Tsinghai, China	7.9	200,000
1932	Gansu, China	7.6	70,000
1933	Honshu, Japan	8.9	3,000
1935	Quetta, Pakistan	7.5	60,000
1939	Erzincan, Turkey	8.0	33,000
1945	Iran and Pakistan	8.2	4,000
1948	USSR	7.9	110,000
1950	India and China	8.6	1,500
1952	Hokkaido, Japan	8.6	600
1952	Alerce, Chile	8.5	2,000
1960	Alaska, USA	8.5	115
1964	Moro, Philippines	8.0	6,500
1976	Tangshan, China	7.5	255,000
1976	Sunda, Indonesia	8.0	200
1977	Bucharest, Romania	7.2	1,600
1985	Mexico City	8.1	5,000
1990	Kobe, Japan	6.8	6,400
1995	Turkey	7.7	17,000
1999	India	7.7	20,000
2004	Sumatra (tsunami)	9.0	283,000
2005	Azad Kashmir, Pakistan	7.6	80,000
2010	Haiti	7.0	200,000
2010	Chile	8.8	600

Source: From U.S. Geological Survey Earthquake Hazards Program, by USGS, U.S. Geological Survey Library.

3.8 FACTORS THAT AFFECT EARTHQUAKE LOADS

The ground motion caused by an earthquake consists of random vibrations. Like any other vibration, this motion is also characterized by its amplitude and frequency. Although the Richter scale gives the total energy released, it provides no information about the characteristics of ground motion (frequency and duration of vibrations) and the interaction of ground vibration with the vibrational characteristics of the building and the underlying soil. Therefore, the Richter scale cannot be used in determining earthquake loads on buildings. Instead, the following factors must be considered:

- Ground motion
- Building's mass and ductility of the structural frame
- Type of soil
- Building occupancy's risk category

GROUND MOTION

To understand how an earthquake impacts a building, imagine a building just before the earthquake. Every part of the building is in static equilibrium. As soon as the earthquake occurs, the ground is displaced horizontally. Because the building has inertia, it takes a finite period of time for the horizontal displacement to travel to the upper parts of the building. In the meantime, the building is subjected to deformations, as indicated by its deformed shape, Figure 3.21. Thus, although there are several differences between the effects of an earthquake and a windstorm on a building (see Section 3.9), the overall building deformation produced by both is similar.

An earthquake results in ground acceleration due to an abrupt ground motion. This acceleration produces an inertial force in the building. This force, which tends to oppose the ground motion, is referred to as the *total earthquake load* on the building. The magnitude of the total earthquake load can be obtained from Newton's second law of motion. According to this law, when a body is accelerated, the inertial force (F) acting on it is equal to the product of the acceleration and the mass of the body:

$$F = ma$$

where m is the mass of the body and a is the acceleration imparted to it.

When Newton's law is applied to buildings, m refers to the mass of the building and a refers to the acceleration of the ground. If ground acceleration is small, the earthquake load is small. This is obvious because if the ground moves very slowly (with negligible acceleration), the building will simply go along with this motion as one unit, and the opposing inertial force (the earthquake load) will be small. In the case of a sudden and swift motion (large acceleration), the lower part of the building moves horizontally, whereas the upper part remains in its original position (see Figure 3.21). In an effort to maintain the status quo, a large opposing (inertial) force is produced in the building—that is, the total earthquake load on the building is large.

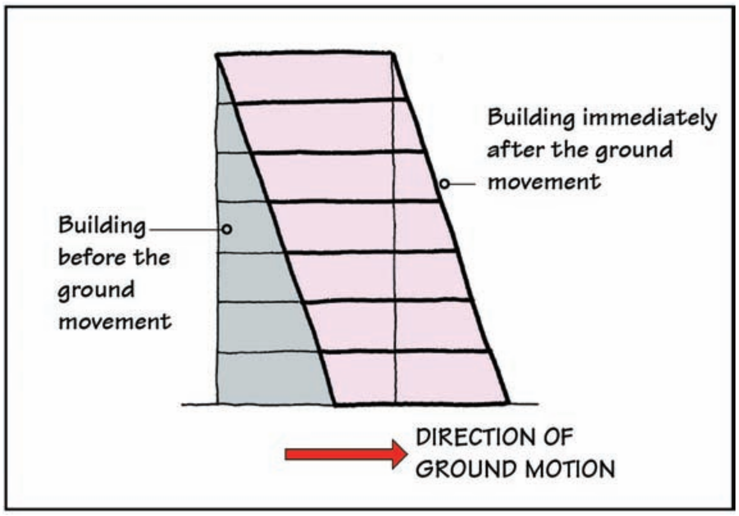

Building immediately after the ground movement
Building before the ground movement
DIRECTION OF GROUND MOTION

FIGURE 3.21 Deformation of building resulting from ground movement. Observe that deformation caused by an earthquake is essentially similar to that caused by wind. Therefore, the structural provisions for earthquake and wind load resistance are essentially similar. In the building shown, similar deformation would have occurred from wind blowing from the right hand side.

BUILDING'S MASS AND DUCTILITY OF THE STRUCTURAL FRAME

From Newton's second law of motion, the other factor that affects the magnitude of the earthquake load is the weight of the building because the weight is directly related to mass. Lighter buildings attract a smaller earthquake load than buildings constructed of heavy materials. Thus, concrete frame and masonry structures attract a greater earthquake load than wood frame or steel frame structures. Residential structures with wood siding or stucco finishes attract a smaller earthquake load than those with brick or stone veneer.

Indeed, because of its light weight, the earthquake load on a tent is negligible even in a severe earthquake, Figure 3.22. A tent structure has the additional advantage of its built-in

FIGURE 3.22 A tent resists earthquake forces admirably due to its light weight and its ability to absorb deformations.

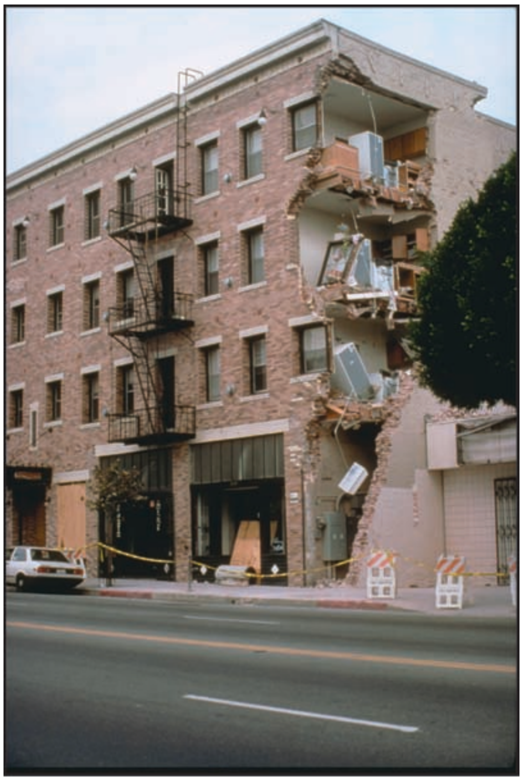


FIGURE 3.23 Damage to an unreinforced masonry building in Santa Monica from the Northridge (California) earthquake on January 17, 1994.
(Photo obtained from NGDC/J. Dewey/U.S. Geological Survey/NOAA)

resistance to absorb structural deformations (ductility)—an important structural property for earthquake regions.

Buildings constructed of heavy materials with little or no capacity to absorb deformations are among the most hazardous buildings in a seismically active zone. Such buildings include those whose structural system consists of unreinforced masonry structures (i.e., brick, stone, or concrete block walls with no vertical reinforcement), Figure 3.23.

SOIL TYPE AND RISK CATEGORY OF THE BUILDING'S OCCUPANCY

The effect of soil on earthquake load is described in Section 11.3. The risk category of the building's occupancy has the same importance as for wind and snow loads; that is, occupancies with above-average risk must be designed for a higher earthquake load than occupancies with average or below-average risk.

3.9 WIND VERSUS EARTHQUAKE RESISTANCE OF BUILDINGS

As discussed in Section 3.4, many of the structural strategies used for wind load resistance and earthquake resistance are essentially similar. Buildings are, therefore, generally designed to resist either earthquake loads or wind loads, whichever causes the worst effect (greater stresses). This is based on the assumption that there is a negligible probability of maximum wind speeds occurring at the same time as an intense earthquake. In regions of low seismic activity, wind loads govern the design of the lateral resistance of buildings; in regions of intense seismic activity, the reverse is the case.

The design of lightweight envelope components, such as glass curtain walls and roof membranes, is governed by wind loads even in highly seismic regions. (Remember that earthquake loads are influenced by the weight of the component.)

Despite the similarities between the provisions for wind load and earthquake load resistance, there are several differences in the details. An important difference is that as an earthquake shakes the ground on which the building rests, it affects all components of the building—exterior as well as interior components. Damage to the building's contents and injury to occupants may occur by falling interior contents, Figure 3.24. Thus, all components, equipment, and fixtures in a building located in a seismically active zone must be adequately anchored to remain intact during an earthquake.

Wind, on the other hand, acts on the building envelope. It is through the envelope that wind loads are transmitted to the building structure. If the envelope remains intact, the building will generally retain its overall structural integrity in a storm. Thus, the wind damage in a building usually begins with the damage to envelope components, such as the roof, exterior walls, exterior doors, windows, and other cladding elements. Once the building changes from fully enclosed to partially enclosed (see Figure 3.15), the wind loads on the building

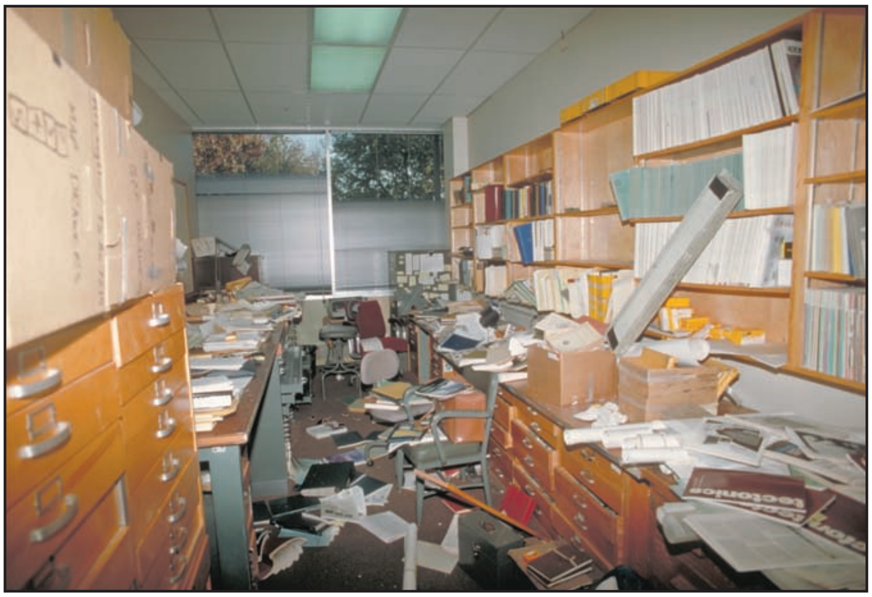


FIGURE 3.24 Effect of earthquake shaking (1989 Loma Prieta earthquake) on the contents of a building's interior. Note that the building envelope is intact. Greater damage could have occurred if the interior fixtures were inadequately anchored.
(Photo obtained from USGS, U.S. Geological Survey Library)

increase due to the ballooning effect, which may result in additional damage or collapse of the structure, damage to interior contents, and injuries to occupants, Figure 3.25.

DISTINCT DESIGN APPROACHES

The more important difference between wind and earthquake resistance lies in their basic design approaches. For wind load resistance, the structure is designed so that under the action of maximum wind loads, it remains elastic—that is, the structure is designed to suffer no permanent deformation under the worst expected storm.

The design approach is different for earthquake load resistance. The loads on a building produced by the worst expected earthquake for the location are so large that if the building were designed to remain elastic after the earthquake, it would be prohibitive in cost. Therefore, the earthquake loads for which a building is designed may be smaller than the maximum earthquake loads expected on it.

The underlying design philosophy is that the building should remain elastic when resisting minor earthquakes. In the event of an intense earthquake, part of the earthquake's energy may be dissipated in permanently deforming the building, but the building must otherwise remain intact to provide complete safety to its occupants.

Permanent deformations in a structure are possible only if the structure has the ability to sustain such deformations. As we will see in Chapter 4, materials that can sustain permanent deformation prior to failure are called *ductile* materials. Ductility is an essential property for buildings located in seismic zones but is not a requirement for resisting wind loads.

A building must not deform permanently even in the most severe windstorm. Additionally, it must be rigid enough to reduce the deflections caused by strong winds. The swaying of the upper floor of tall buildings under wind loads must be controlled to remain within acceptable limits of human tolerance.

The reverse is true for earthquake loads. Buildings must be able to deform, even permanently, to absorb the energy delivered to them by the earthquake. If brittle materials are used, they will fail under earthquake forces. Several reinforced concrete frame buildings with (brittle) unreinforced masonry infill walls between frames have collapsed or suffered serious damage under earthquake forces, Figure 3.26. Such buildings would generally be unharmed by violent storms.

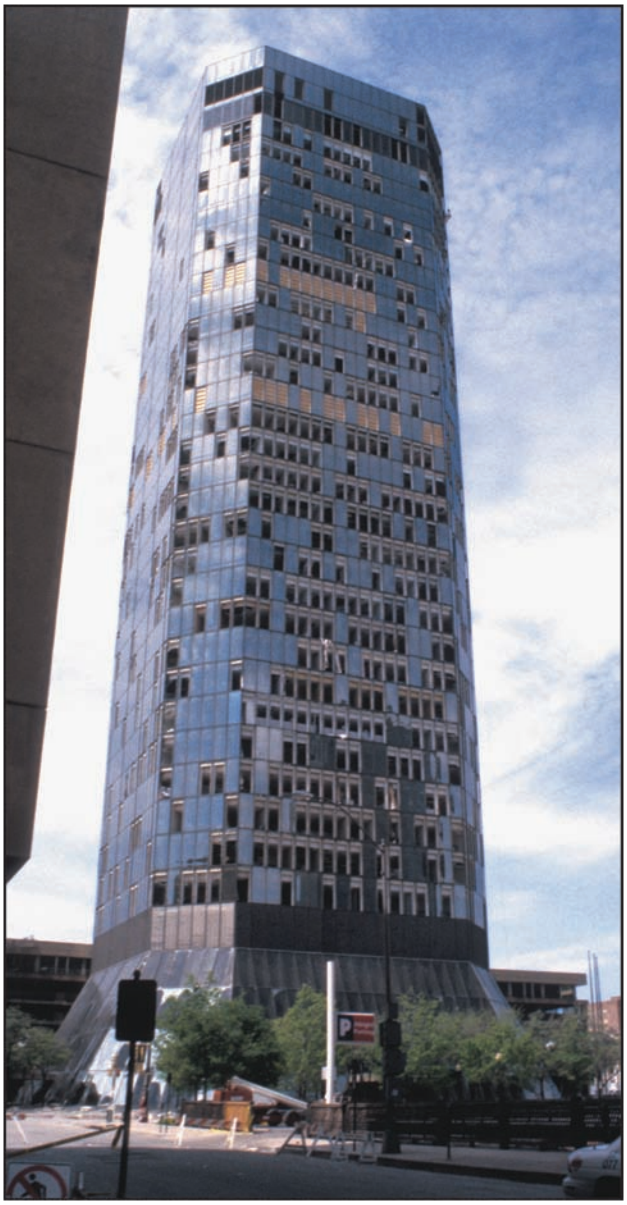


FIGURE 3.25 Damage to the glass curtain wall of the 37-story Bank One Building, Fort Worth, Texas, by a forceful tornado on March 28, 2000. As soon as the glass in the curtain wall shattered, substantial damage to the building's interior (ceiling, drywall, electrical fixtures, etc.) occurred.

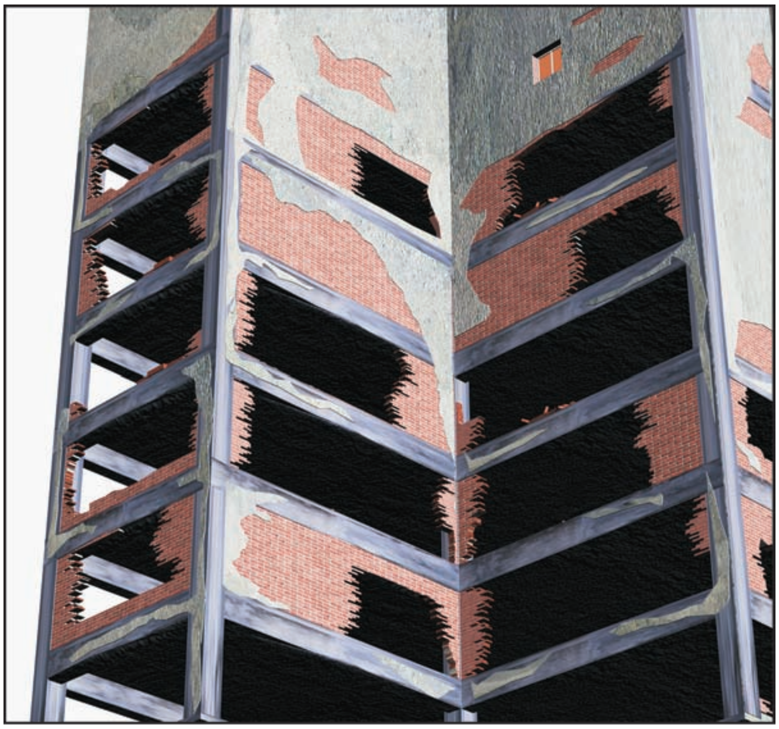


FIGURE 3.26 A typical pattern of damage to unreinforced masonry infill walls in buildings with a reinforced concrete frame structure. If the infill walls shown in this illustration had been reinforced horizontally and vertically, they would have suffered minor (or no) damage depending on the earthquake's intensity.

PRINCIPLES IN PRACTICE

Dead Load and Live Load Estimation

TRIBUTARY AREA OF A BUILDING COMPONENT

In computing the dead loads and other loads on a component, the concept of *tributary area* is important to understand. The tributary area for a component is the area (or areas) of the building that *contributes* load on that component.

For example, in a floor system that consists of wood planks supported by parallel beams, the tributary area for a beam is the area of the floor that lies halfway to the adjacent beam on the left and halfway to the adjacent beam on the right. In Figure 3.27, the tributary area for beam A is shown by the colored area. All the load that is placed on this colored area must be carried by beam A.

The tributary area for a column in a building is similarly obtained. In the framing plan of the building shown in Figure 3.28, the tributary areas of an interior column X, an exterior column Y, and a corner column Z have been colored. Thus, column X receives all the load placed on the colored area of the floor surrounding it. This is a rectangular area with dimensions $0.5(L_1 + L_2)$ by $0.5(W_1 + W_2)$. Thus, if L_1 and L_2 are 12 ft and 18 ft, respectively, and W_1 and W_2 are each 13 ft, the tributary area for column X is 15 ft × 13 ft.

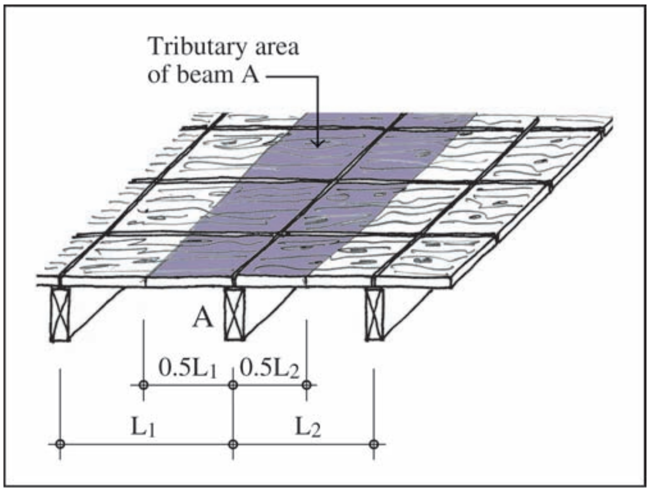


FIGURE 3.27 The tributary area of beam A is the colored area. The width of this area $= 0.5(L_1 + L_2)$, where L_1 and L_2 are the center-to-center distances between beams.

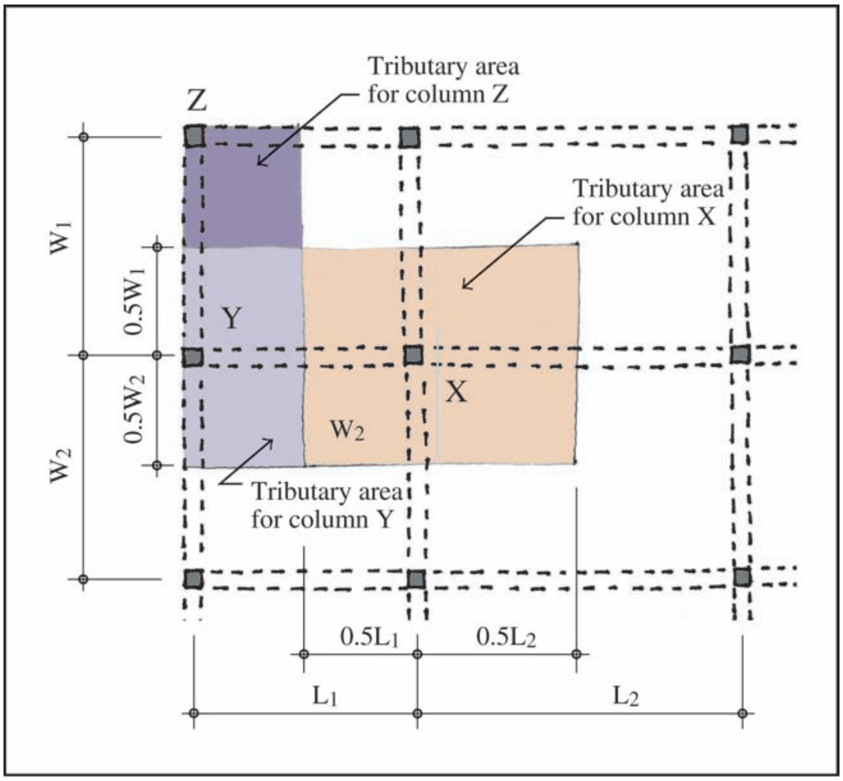


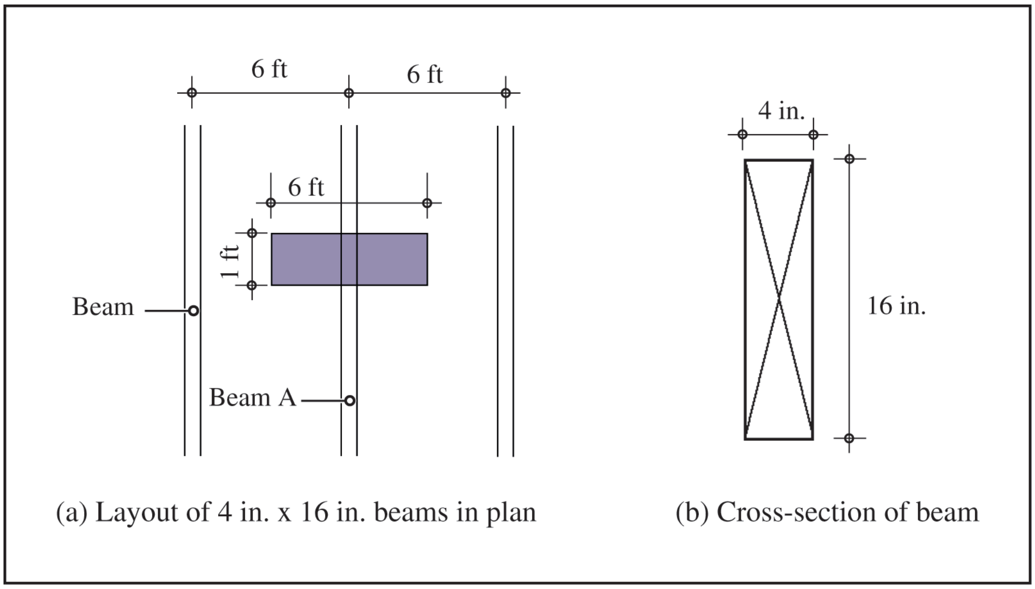
FIGURE 3.28 Tributary areas for columns X, Y, and Z.

EXAMPLE 3.1 (ESTIMATING THE DEAD LOAD ON A BEAM)

Determine the dead load on beam A of Figure 3.29, where each (wood) beam is 4 in. × 16 in. in cross section and is spaced 6 ft on center. The (wood) floor planks are $2\frac{1}{2}$ in. thick. Assume that the density of wood is 40 lb/ft^3 (pcf).

SOLUTION

Because the load on a beam is generally expressed in pounds/foot, we will isolate a 1-ft length of beam A and determine all the dead load on this length. What holds for this 1-ft length also holds for the rest of the beam.


6 ft
6 ft
6 ft
1 ft
Beam
Beam A
4 in.
16 in.

(a) Layout of 4 in. x 16 in. beams in plan

(b) Cross-section of beam

FIGURE 3.29 Refers to Example 3.1.

$$\text{Volume of a 1-ft-long beam} = \left(\frac{4}{12}\right)\left(\frac{16}{12}\right)(1) = 0.44 \text{ ft}^3$$

$$\text{Weight of a 1-ft-long beam} = 0.44(40) = 17.6 \text{ lb}$$

From Figure 3.29, the tributary area of a 1-ft-long beam is 1 ft × 6 ft $= 6.0 \text{ ft}^2$. Hence, the weight of 6 ft^2 of floor planks is borne by a 1-ft-long beam.

$$\text{Volume of } 6.0 \text{ ft}^2 \text{ planks} = (6.0)\left(\frac{2.5}{12}\right) = 1.25 \text{ ft}^3$$

$$\text{Weight of planks} = 1.25(40) = 50.0 \text{ lb}$$

The total dead load on beam A $= 17.6 + 50.0 = 67.6$ lb/ft.

EXAMPLE 3.2 (ESTIMATING THE DEAD LOAD OF A TYPICAL WOOD FRAME RESIDENTIAL FLOOR)

Determine the dead load of a typical residential floor constructed of 2×12 (nominal) Douglas fir floor joists spaced 16 in. on center. The subfloor consists of $\frac{3}{4}$-in.-thick plywood and a $\frac{1}{4}$-in.-thick hardboard underlayment, Figure 3.30. Vinyl tiles are used as floor finish, and the ceiling consists of $\frac{1}{2}$-in.-thick gypsum wallboard.

Note: A (nominal) 2×12 floor joist has actual dimensions of $1\frac{1}{2}$ in. $\times\, 11\frac{1}{4}$ in.

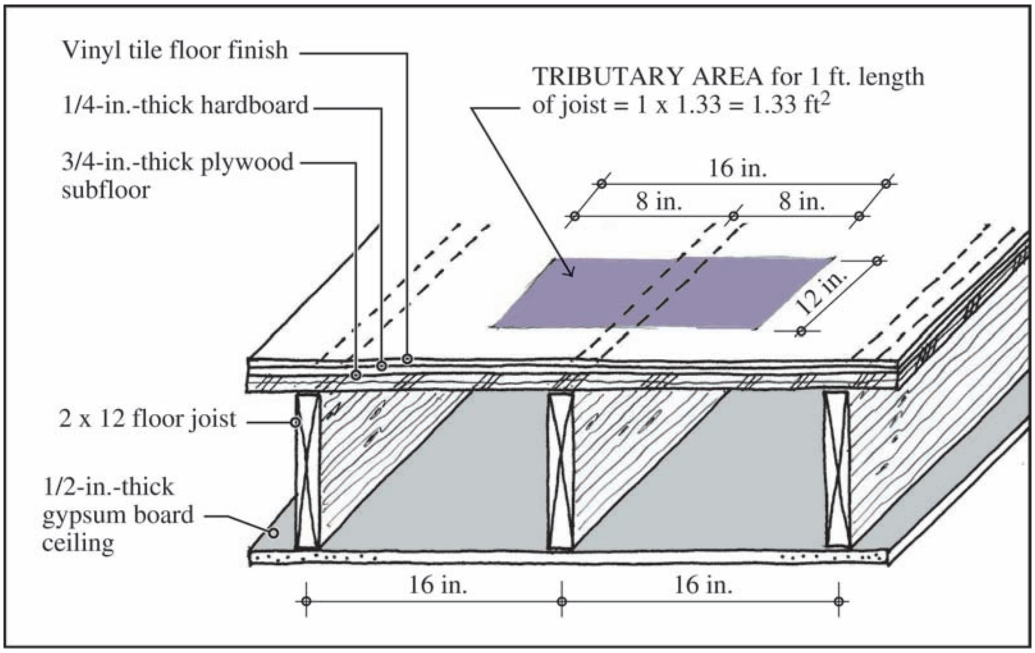

Vinyl tile floor finish
1/4-in.-thick hardboard
3/4-in.-thick plywood subfloor
TRIBUTARY AREA for 1 ft. length of joist = 1 x 1.33 = 1.33 ft²
16 in.
8 in.
8 in.
12 in.
2 x 12 floor joist
1/2-in.-thick gypsum board ceiling
16 in.
16 in.

FIGURE 3.30 Floor and ceiling construction in a typical wood frame residential building, refers to Example 3.2.

(Continued)

PRINCIPLES IN PRACTICE

Dead Load and Live Load Estimation (*Continued*)

SOLUTION

A simple method for solving this problem is to add the weights of 1 ft^2 of all sheet materials of the floor system: vinyl tiles, hardboard underlayment, plywood subfloor, and gypsum board. From Table 3.5, these weights are as follows:

Vinyl tiles	1.0 lb
Hardboard (2 × 0.4)	0.8 lb
Plywood (6 × 0.4)	2.4 lb
Gypsum board (4 × 0.55)	2.2 lb
Total weight	6.4 lb

Thus, the total load due to all sheet materials of the floor system is 6.4 lb/ft^2. To this weight, if we add the weight of the floor joist, we will obtain the dead load of the entire floor assembly.

The weight of a 1-ft-long floor joist can be calculated by multiplying the volume of the joist by the density of Douglas fir, which is 34 lb/ft^3, Table 3.6.

$$\text{Volume of a 1-ft-long joist} = \left(\frac{1.5}{12}\right)\left(\frac{11.25}{12}\right)(1) = 0.12 \text{ ft}^3$$

$$\text{Weight of a 1-ft-long joist} = (0.12)(34) = 4.1 \text{ lb}$$

TABLE 3.5 APPROXIMATE (SURFACE) DENSITIES OF SELECTED MATERIALS

Component	Weight lb/ft^2	Component	Weight lb/ft^2
Roof Coverings		Plywood or hardboard (per $\frac{1}{8}$-in. thickness)	0.4
Asphalt shingles	2.0	Linoleum, vinyl, or asphalt tile ($\frac{1}{4}$-in. thick)	1.0
Clay tiles	12–18	Marble or slate or terrazzo (per 1-in. thickness)	12
Gravel-covered built-up roof	4.0	Granite	15
Insulation (per 1 in. thickness)		Ceilings	
Fiberglass	0.1–0.2	Gypsum board (per $\frac{1}{8}$-in. thickness)	0.55
Extruded or expanded polystyrene, or polyurethane or polyisocynurate	0.2	Plaster on wood lath	8.0
		acoustical fiber tile	1.0
Floors and Floor Finishes		Mechanical duct allowance	4.0
Hardwood flooring, $\frac{7}{8}$-in. thick	4.0		

TABLE 3.6 APPROXIMATE (VOLUME) DENSITIES OF SELECTED MATERIALS

Material	Weight, lb/ft^3	Material	Weight, lb/ft^3
Metals		Wood	
Cast iron	450	Oak	47
Copper	556	Douglas fir	34
Lead	710	Hem fir	28
Steel	490	Southern pine	37
Zinc	450	Wood Products	
Cement and Concrete		Plywood	36
Concrete (normal weight)	145	Particleboard	45
Reinforced concrete (normal weight)	150	Gypsum Products	
Structural lightweight concrete	85–115	Gypsum wallboard	50
Insulating concrete	25–50	Lath and plaster	55
Portland cement	94	Insulating Materials	
Lime	45	Fiberglass	1.0–2.5
Masonry		Rockwool	1.0–2.5
Clay brick	110–130	Extruded or expanded polystyrene	2.0
Concrete block (lightweight)	105–125	Polyisocyanurate	2.0
Concrete block (normal weight)	135	Glass (flat glass)	160
Masonry mortar or grout	130	Earth	
Stone		Clay, silt, or sand (dry packed)	100
Granite	165	Crushed stone	100–120
Limestone	165	Water	63
Marble	170	Ice	57
		Air	0.075

PRINCIPLES IN PRACTICE

From Figure 3.30, a 1-ft-long floor joist carries 1.33 ft^2 of floor.

Therefore, the weight of floor joist that contributes to 1 ft^2 of the floor is $\left(\frac{4.1}{1.33}\right) = 3.1$ lb.

Hence, the total dead load of 1 ft^2 of floor is $6.4 + 3.1 = 9.5$ lb.

This is an important result because the dead load of a conventional wood frame floor is assumed to be 10 psf.

EXAMPLE 3.3 (ESTIMATING THE TOTAL GRAVITY LOAD ON A TYPICAL WOOD FRAME RESIDENTIAL FLOOR)

Determine the total gravity load (dead load + live load) on the floor of Example 3.2. The floor is part of an apartment building.

SOLUTION

The dead load of the floor is 10 psf, Example 3.2.
The live load on a residential floor is 40 psf, Table 3.5.
Hence, the total gravity load (dead load + live load) is $10 + 40 = 50$ psf.

EXAMPLE 3.4 (ESTIMATING THE DEAD LOAD OF A WOOD FRAME RESIDENTIAL FLOOR WITH LIGHTWEIGHT CONCRETE TOPPING)

In many multifamily dwellings, a lightweight concrete topping is used over a wood floor to increase the sound insulation between floors. Determine the dead load of such a floor, assuming $1\frac{1}{2}$-in.-thick lightweight concrete topping. The density of lightweight concrete is 100 pcf.

SOLUTION

The dead load of a typical residential wood floor is 10 psf, Example 3.2.

Volume of 1 sq ft of concrete topping $= 1.0 \times 0.125 = 0.125$ ft^3 (Note that $1\frac{1}{2}$ in. $= 0.125$ ft)

Weight of 1 sq ft of concrete topping $= 0.125 \times 100 = 12.5$ lb

Hence, the total dead load of the floor is $10 + 12.5 = 22.5$ psf.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

23. According to the geologists, the earth's surface is composed of several segments that are called
- **a.** earth segments.
- **b.** surface plates.
- **c.** tectonic plates.
- **d.** geological segments.
- **e.** segmental plates.

24. The region of the United States that is relatively more earthquake prone is the
- **a.** northern United States.
- **b.** southern United States.
- **c.** eastern United States.
- **d.** western United States.
- **e.** none of the above.

25. The number of mild (minor to very minor) earthquakes occurring on the earth is almost
- **a.** 1 or 2 per year.
- **b.** 10 to 20 per year.
- **c.** 100 per year.
- **d.** 1,000 per year.
- **e.** several thousand per year.

26. An earthquake measuring 7.0 on the Richter scale is
- **a.** twice as strong as a 6.0 earthquake.
- **b.** 10 times stronger than a 6.0 earthquake.
- **c.** 100 times stronger than a 6.0 earthquake.
- **d.** 500 times stronger than a 6.0 earthquake.
- **e.** none of the above.

27. Everything else being the same, a building constructed of heavyweight materials is subjected to a greater earthquake load than a building constructed of lightweight materials.
- **a.** True
- **b.** False

28. A reinforced concrete beam measures 12 in. × 24 in. in cross section. If the density of reinforced concrete is 150 lb/ft^3, the weight of the beam is
- **a.** 450 lb/ft.
- **b.** 350 lb/ft.
- **c.** 300 lb/ft.
- **d.** 300 lb.
- **e.** 300 lb/ft^3.

29. In a building whose structural system consists of columns, beams, and floor and roof slabs, the columns are spaced at 40 ft on center in one direction and 25 ft on center in the other direction. What is the tributary area for an interior column?
- **a.** 1,000 ft^2
- **b.** 1,000 ft
- **c.** 500 ft^2
- **d.** 250 ft^2
- **e.** None of the above

(*Continued*)

30. In a building whose structural system consists of columns, beams, and floor and roof slabs, the columns are spaced at 40 ft on center in one direction and 25 ft on center in the other direction. What is the tributary area for a corner column?

a. 1,000 ft^2 **b.** 1,000 ft
c. 500 ft^2 **d.** 250 ft^2
e. None of the above

31. The total approximate dead load of a floor in a typical wood frame residential building is

a. 50 psf. **b.** 30 psf.
c. 10 psf. **d.** 5 psf.
e. none of the above.

32. The total approximate gravity load on a floor in a typical wood frame residential building is

a. 50 psf. **b.** 30 psf.
c. 10 psf. **d.** 5 psf.
e. none of the above.

REVIEW QUESTIONS

1. What is the difference between: (a) dead load and live load, (b) floor live load and roof live load, and (c) roof live load and rain load. Explain with the help of examples.
2. What is the approximate wind speed in a tornado? Explain why tornado wind speeds are not considered in determining the design wind speed for a location.
3. Using sketches and notes, explain the types of wind pressure that occur on a rectangular building.
4. Using sketches and notes, explain how roof slope affects wind pressure on a roof.
5. What is the design wind speed for average-risk building: (a) for most locations in the United States and (b) for coastal areas of the western United States.
6. Explain the differences between wind Exposure Categories B, C, and D.
7. Using sketches and notes, explain the ballooning effect in buildings.
8. What is the Richter scale and what does it measure? What is the difference between the amounts of energy released by two earthquakes that are 8.0 and 6.0 on the Richter scale? Show calculations.
9. What types of construction are (a) suitable and (b) unsuitable in an earthquake-prone region? Explain your answer, giving reasons.
10. Explain the major differences between designing buildings for earthquake resistance and for wind resistance.

CHAPTER 4

Load Resistance (The Structural Properties of Materials)

CHAPTER OUTLINE

4.1 Compressive and Tensile Strengths of Materials

4.2 Ductility and Brittleness

4.3 Yield Strength of Materials

4.4 Elasticity and Plasticity

4.5 Modulus of Elasticity

4.6 Bending Strength of Materials

4.7 Shear Strength of Materials

4.8 Bearing Strength of Materials

4.9 Structural Failures

4.10 Structural Safety

The history of the development of architectural form coincides with the evolution of human understanding of the structural properties of materials and their application to the design and construction of buildings. Every civilization has found it necessary to understand the strength and limitations of indigenous materials in order to design safe and durable structures. The small spans of beams used in Greek temples, as shown in Figure 4.1, were due mainly to the designer's instinctive understanding that stone is a brittle material that is weak in tension and would break if the span is too long or the beam size is too small.

Stone's high strength in compression was exploited in columns and walls, but the column spacings and the sizes of openings in walls had to be small. Although the main reason for providing capitals at the tops of columns in Greek temples was nonstructural, the capitals provided greater structural safety by reducing beam spans even further.

The discovery of the arch—a form that carries loads primarily in compression—enabled early builders to span greater distances in stone (or brick) than was previously possible. The arch led to the development of the vault, which is essentially a three-dimensional version of the arch, and subsequently to the dome—a form obtained by rotating the arch about a center point.

The arch, the vault, and the dome dominated architecture for centuries as the primary form-giving elements in buildings because the major construction materials available at the time, such as stone and brick, were brittle materials. The use of wood, which is less brittle than stone, was limited to either minor buildings or minor components of buildings because of its lack of durability. Sooner or later, wood structures were either consumed by fire or destroyed by termites.

Masonry buildings, on the other hand, are extremely durable, and some have survived for thousands of years. Therefore, the formal, intellectual, and technological use of brittle materials became highly perfected over time. Gothic cathedrals are excellent examples of how the

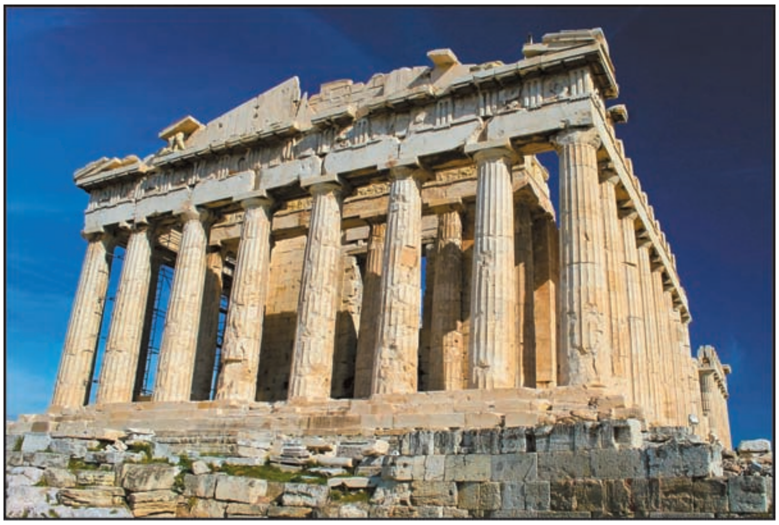


FIGURE 4.1 Parthenon, Acropolis, Greece. Observe the relatively small span of beams in response to the weakness of stone in bending.
(Photo by Brent Wong/Shutterstock)

limitations in the tensile strength of brittle materials were overcome to produce magnificent and technically daring structures, Figure 4.2.

The Industrial Revolution brought many new developments in architectural form. The availability of wrought iron and, later, cast iron had already revived the beam as a horizontal spanning element because of iron's high tensile strength. Large openings became possible without the use of arches, and the progression from load-bearing masonry buildings to the skeleton frame did not require much imagination. After steel became commercially available (in the mid-nineteenth century), the frame structure replaced load-bearing masonry as the predominant structural system.

The invention of new materials—prestressed concrete, high-strength steels, reinforced concrete, and concrete masonry—led to the development of new structural forms. In fact, the modern movement and subsequent developments in architecture owe a great deal to the exploitation of the structural properties of materials.

In this chapter, we examine some of the important properties that influence the strength of materials. Emphasis is placed on properties that relate directly to the basic structural materials, such as steel, concrete, brick, stone, and wood. However, the principles examined have general application.

Structural properties of materials and the behavior of structures under loads cannot be divorced from each other. They are so interrelated that often the distinction between the two is vague at best. Ductility and brittleness, elasticity, and plasticity, which are properties of materials, are also used to describe the behavior of an entire structure or components of a structure. Therefore, structural behavior is discussed in this chapter where necessary to describe the structural properties of materials.

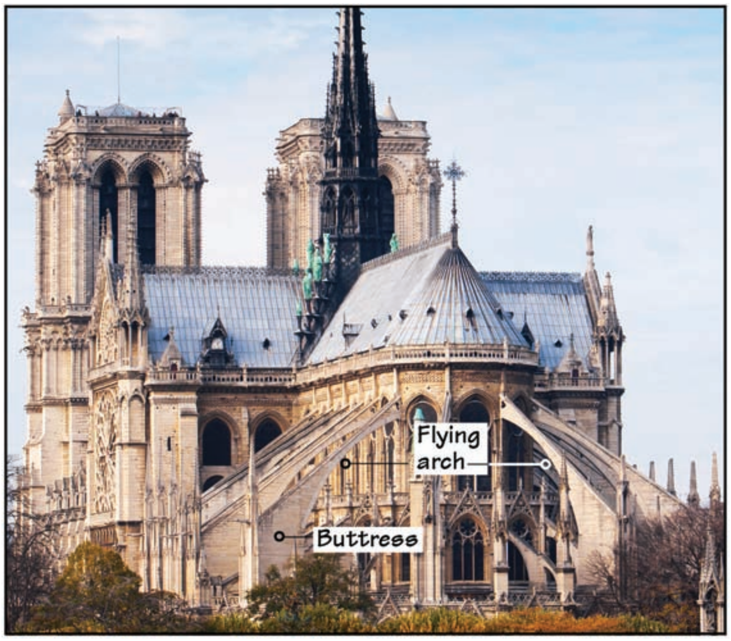


FIGURE 4.2 Cathedral of Notre Dame de Paris, completed in 1262. Buttresses and flying arches were some of the structural elements used in major buildings at the time, giving birth to the architectural style known as *Gothic Architecture*. The flying arches shifted the lateral thrust, created by the vaulted roofs above, away from the building and transferred it to the buttresses. The buttresses provided the dead load to counter the lateral thrust—an innovation that resulted from the realization that stone masonry has a limited ability to resist tensile stresses.
(Photo by Slavko Sereda/Shutterstock)

4.1 COMPRESSIVE AND TENSILE STRENGTHS OF MATERIALS

When a force acts on a member (such as a building component), the member develops an internal resistance to the applied force. The intensity of internal resistance to the applied external force is called the *stress*. If the applied force is large, the internal resistance is large, and so is the stress. If the applied force is small, the stress developed in the member is also small.

If a member is unable to develop any resistance to an applied force, the stress in the member is zero. For instance, if we hold a cable (or rope) between two hands and push it inward, that is, put a compressive force on the cable, we observe that it does not resist the applied force and simply gives in, Figure 4.3(a). The (compressive) stress in the cable in this case is zero.

If, on the other hand, the cable is pulled, that is, a tensile force is applied on the cable, the cable tends to resist the force and becomes taut, implying the existence of tensile stress in the cable, Figure 4.3(b). The stress in the cable increases as the applied tensile force is increased.

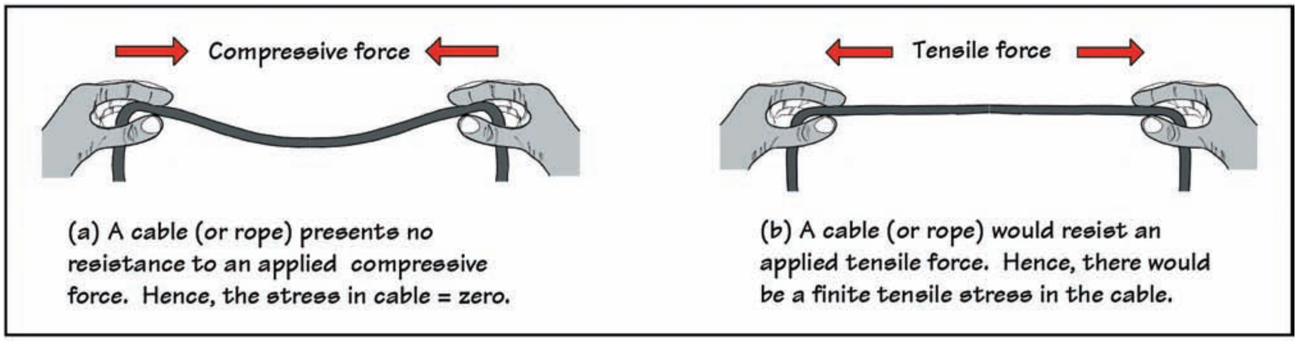

Compressive force
Tensile force
(a) A cable (or rope) presents no resistance to an applied compressive force. Hence, the stress in cable = zero.
(b) A cable (or rope) would resist an applied tensile force. Hence, there would be a finite tensile stress in the cable.

FIGURE 4.3 Stresses in a cable under **(a)** an applied compressive force and **(b)** an applied tensile force.

From this example, we learn that the stress can either be compressive or tensile, depending on the type of external force. If the external force is compressive, the stress created in the member is *compressive stress* (or simply *compression*), and if the external force is tensile, the stress created in the member is *tensile stress* (or simply *tension*). A column or wall in a typical building is in compression, Figure 4.4(a). In a simple truss made of two rafters and a ceiling joist, the rafters are in compression and the ceiling joist is in tension, Figure 4.4(b). In a suspension bridge, the vertical pylons are in compression and the suspension cables are in tension, Figure 4.5.

Quantitatively, the stress is defined as the force acting on a unit cross-sectional area (1 in.^{2} or 1 ft^2) of the member. That is why we referred to the stress as the *intensity* of internal resistance. The symbol commonly used for stress is f. Thus,

$$\boxed{f = \frac{\text{force}}{\text{area}} = \frac{P}{A}} \qquad \textbf{Eq. (4.1)}$$

where P = force and A = cross-sectional area of the member.

If the force is expressed in pounds and the cross-sectional area is in square inches, the unit of stress is pounds per square inch (psi). If the force is expressed in kips (1 kip = 1,000 lb), the unit of stress is kips per square inch (ksi).

For instance, if the force applied on the cable of Figure 4.3(b) is 500 lb and if the diameter of the cable is 0.5 in. (cross-sectional area = 0.196 in.^{2}), the tensile stress in the cable is

$$f = \frac{500}{0.196} = 2{,}550 \text{ psi} = 2.55 \text{ ksi}$$

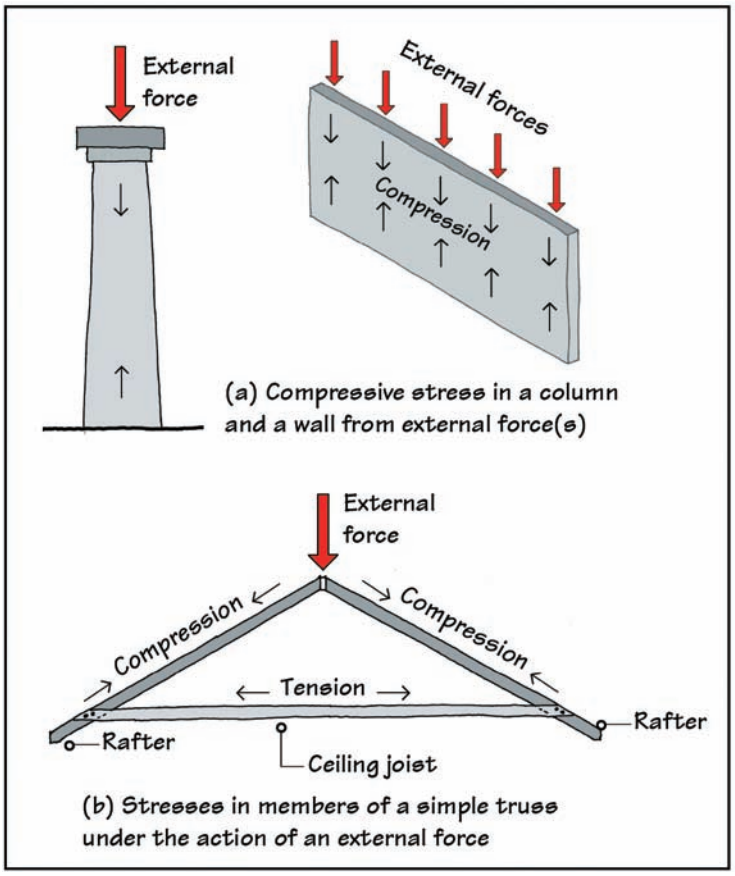
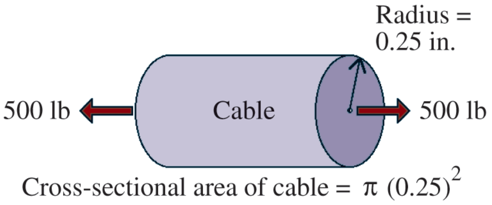

External force
External forces
Compression
(a) Compressive stress in a column and a wall from external force(s)
External force
Compression
Compression
Tension
Rafter
Rafter
Ceiling joist
(b) Stresses in members of a simple truss under the action of an external force

FIGURE 4.4 Compressive and tensile stresses in building components.


Radius = 0.25 in.
500 lb
Cable
500 lb

Cross-sectional area of cable = $\pi\,(0.25)^2$
= 0.196 in.^{2}

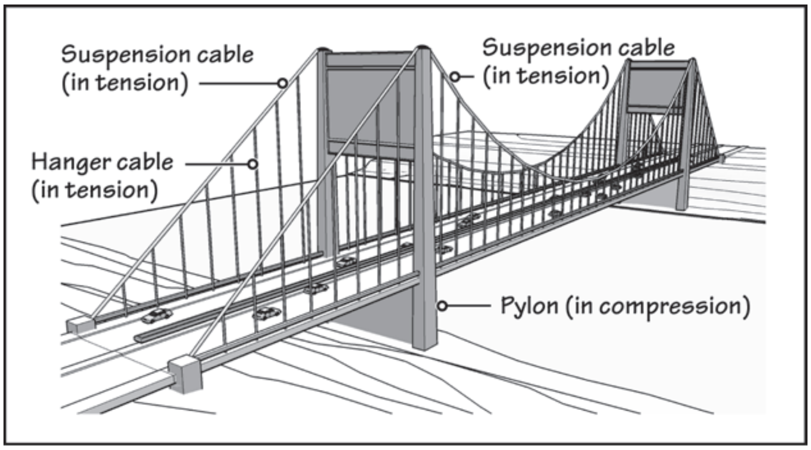

Suspension cable (in tension)
Suspension cable (in tension)
Hanger cable (in tension)
Pylon (in compression)

FIGURE 4.5 Tensile and compressive stresses in the members of a suspension bridge.

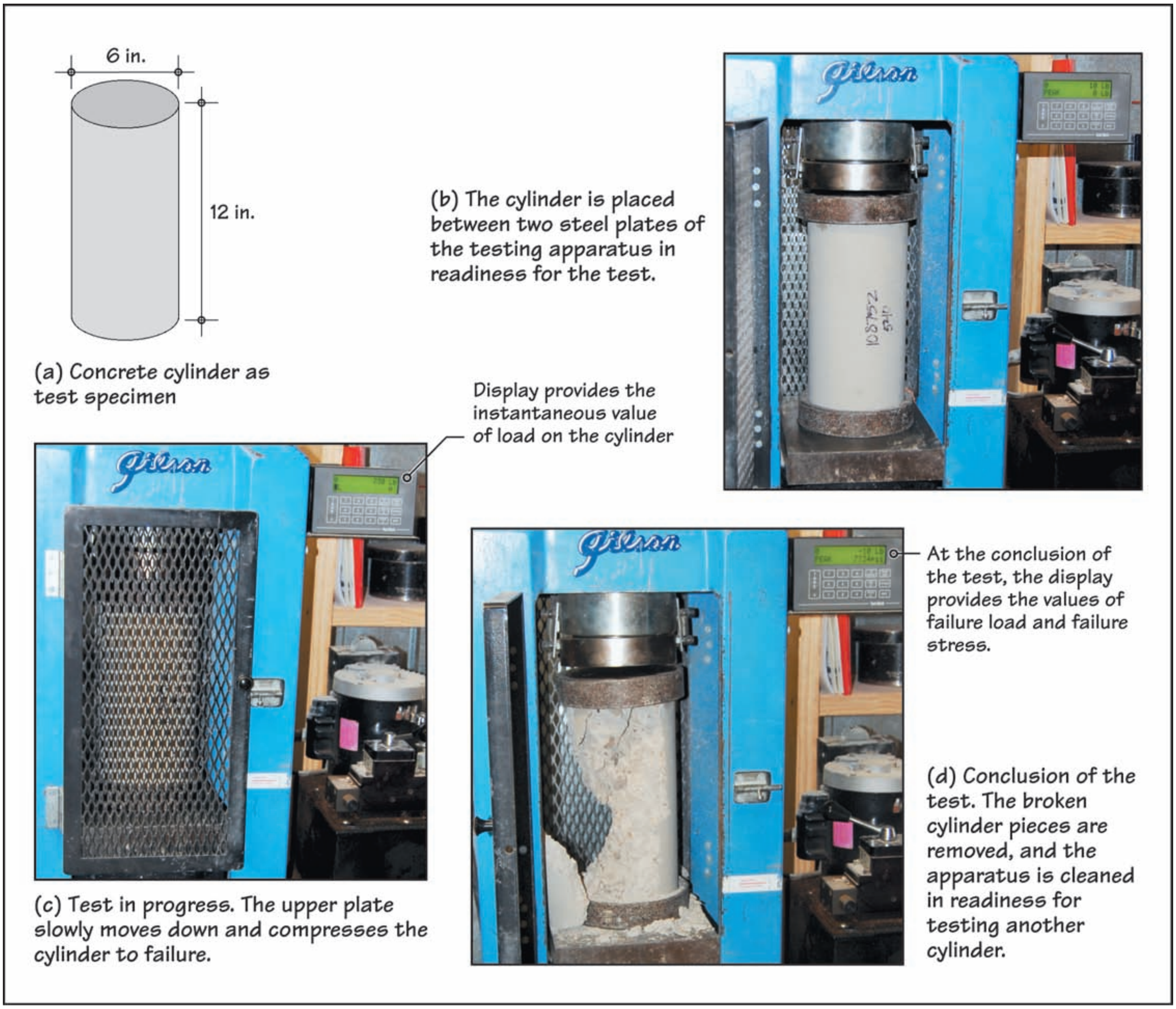
ULTIMATE COMPRESSIVE STRENGTH AND ULTIMATE TENSILE STRENGTH

If the applied force on a member results in its failure, the stress in the member at failure is referred to as the *ultimate stress*, which is also known as *ultimate strength* or simply the *strength* of the material. Thus, if the cable of Figure 4.3(b), with a cross-sectional area of 0.196 in.^{2}, fails when the applied tensile force is 1,000 lb, the *tensile strength* of the cable's material is:

$$\text{Tensile strength} = \frac{1{,}000}{0.196} = 5{,}100 \text{ psi} = 5.1 \text{ ksi}$$

TESTING OF MATERIALS TO OBTAIN THEIR ULTIMATE STRENGTH

Standards such as those mentioned in Chapter 2 prescribe the approved test methods for determining the tensile and compressive strengths of various materials. For example, if we wish to determine the compressive strength of concrete, we perform a standard test. This test involves crushing a 6-in.-diameter cylinder of concrete 12 in. high in a controlled setting, Figures 4.6(a) and 4.6(b). As the load is applied, it is measured and recorded continuously until the cylinder is crushed (fails), Figure 4.6(c). The ultimate compressive strength of the concrete is obtained from the load that caused the failure.



(a) Concrete cylinder as test specimen

(b) The cylinder is placed between two steel plates of the testing apparatus in readiness for the test.

Display provides the instantaneous value of load on the cylinder

(c) Test in progress. The upper plate slowly moves down and compresses the cylinder to failure.

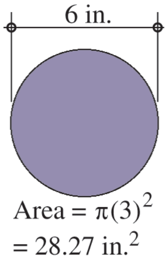
At the conclusion of the test, the display provides the values of failure load and failure stress.

(d) Conclusion of the test. The broken cylinder pieces are removed, and the apparatus is cleaned in readiness for testing another cylinder.

FIGURE 4.6 Apparatus and test specimen (6 in. × 12 in. concrete cylinder) used for determining the compressive strength of concrete.

For instance, in Figure 4.6, let us assume that the cylinder failed when the load reached 115 kips. Then the compressive strength of concrete would be

$$\text{Compressive strength} = \frac{\text{load at failure}}{\text{area of cylinder}} = \frac{115}{28.27} = 4.1 \text{ ksi}$$
$$= 4{,}100 \text{ psi}$$



The method and test setup (machine) for determining the compressive strength of brick or concrete block masonry is similar. The specimen used is a masonry prism of a specified size made from several bricks or blocks with mortar joints, Figure 4.7.

The tensile strength of concrete or masonry is very low compared with its compressive strength—approximately 10% of its compressive strength. Thus, if the compressive strength of concrete is 4,000 psi, its tensile strength is only about 400 psi. That is why the tensile strength of concrete is generally ignored in the design of concrete structures; that is, we assume that the tensile strength of concrete is zero.

We typically determine the tensile strength of steel using a round bar specially machined at the ends to provide a grip for the machine to pull the bar to failure. A commonly used tensile-testing machine is shown in Figure 4.8. The compressive strength of steel is approximately equal to its tensile strength, provided that the steel member is prevented from buckling (see Section 4.9).

4.2 DUCTILITY AND BRITTLENESS

Stress is nearly always accompanied by deformation of the member. The exception to this rule is a *rigid body*. A rigid body is defined as one that does not deform at all under the action of loads. In other words, a rigid body will not stretch, shorten, bend, or change shape regardless of the magnitude of the load placed on it. In the real world, a rigid body does not exist, because all materials deform when loaded. Actual bodies, such as building components, will deform under loads, although the deformations in them are usually too small to be visible to the human eye.

The deformation caused by a compressive or a tensile stress is simply the change in the length of the member. Tensile stress causes the member to elongate, and compressive stress causes it to shorten. We are interested in both the absolute value of the change in length and its relative value. The relative change in length, defined as the change in length divided by the original length, is called the *strain*.

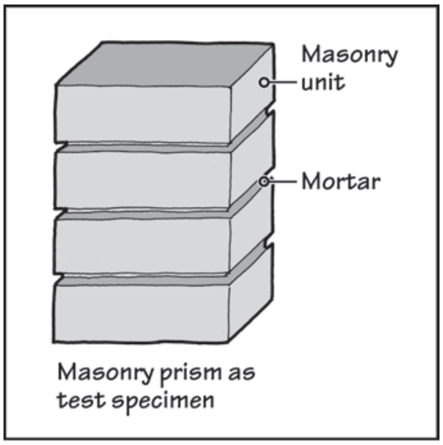


FIGURE 4.7 Test specimen used for determining the compressive strength of masonry.

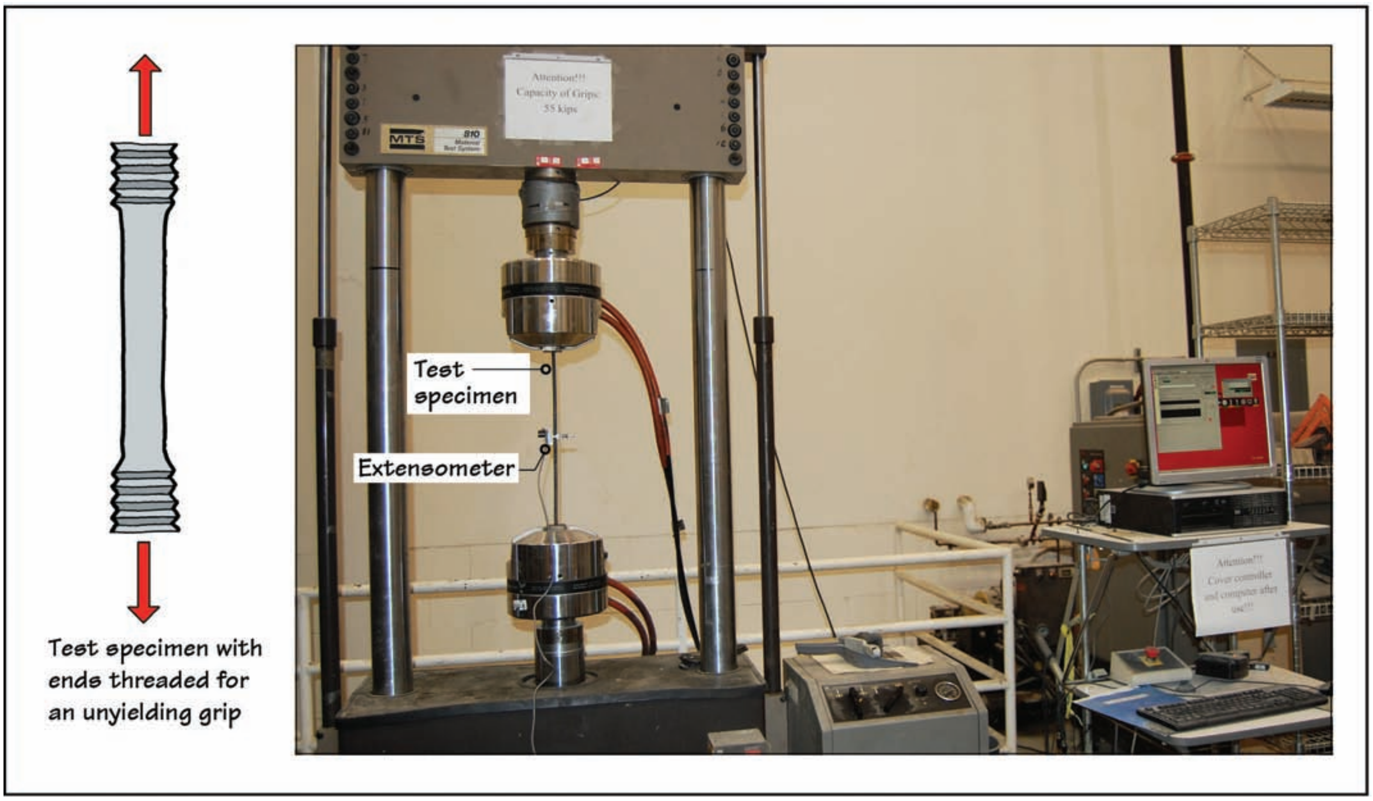

Attention!!! Capacity of Grips: 55 kips
MTS
Test specimen
Extensometer
Test specimen with ends threaded for an unyielding grip

FIGURE 4.8 A typical test setup to measure the tensile strength of a specimen. The clip-on extensometer measures the deformation of the specimen under load.

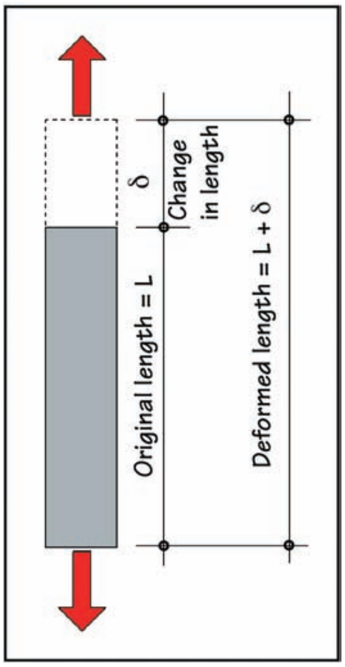


FIGURE 4.9 If a bar, whose original length is L, stretches to length (L + δ) under the action of a force, then the strain in bar, $\varepsilon = (\delta/L)$.

NOTE

Brittle and Ductile Materials

A brittle material is one for which ultimate strain ≤0.5%.

A ductile material is one for which ultimate strain >0.5%.

Thus, in Figure 4.9 if the original length of the bar is L, which—under the action of a tensile force—becomes L + δ, then the strain in the bar, denoted by the Greek letter ε (epsilon), is given by

$$\boxed{\varepsilon = \frac{\text{change in length}}{\text{original length}} = \frac{\delta}{L}} \qquad \textbf{Eq. (4.2)}$$

From Equation (4.2) if a 10-ft (120-in.)-high column shortens by 0.25 in. under a load, the strain in the column is

$$\text{Strain}(\varepsilon) = \frac{0.25}{120} = 0.002$$

Because strain is the ratio of two lengths, it is simply a number with no units of measure. The strain caused by a tensile force is called *tensile strain*; that caused by a compressive force is called *compressive strain*. The strain in the element at failure is referred to as the *ultimate strain*.

The ultimate strain for most building materials is usually small. For example, the ultimate compressive strain of concrete or masonry is approximately 0.003. It is, therefore, more convenient at times to express strain as a percentage. For example, a strain of 0.003 is equal to 0.3% strain. The ultimate strain for mild steel (the term *mild steel* is defined later) is nearly 0.35 (or 35%), which is fairly large. In other words, for mild steel, a 100-in.-long steel bar will elongate by 35 in. at failure; that is, its length will become 135 in.

Materials that produce large deformations before failure are called *ductile materials*. Conversely, materials that do not deform much before failure are called *brittle* materials. The corresponding properties are called *ductility* and *brittleness*. There is no general agreement as to the limiting value of the ultimate strain that distinguishes a ductile material from a brittle material, but we generally regard a material as brittle if its ultimate strain is less than or equal to 0.5%. A ductile material is one whose ultimate strain is greater than 0.5%.

Materials such as brick, stone, concrete, and glass have an ultimate strain of less than 0.5% and are, therefore, classified as brittle materials. Approximate values of ultimate strains of the commonly used structural materials are shown in Figure 4.10.

Most metals are ductile, because they have large deformations at failure. Pure metals are more ductile than their alloys. Pure gold is seldom used in jewelry because it is very ductile and, hence, prone to damage by deformation. The same is true of pure iron. It is too ductile and soft for use as a construction material, but when alloyed with carbon to form steel, it becomes a useful construction material.

BRITTLENESS AND TENSILE STRENGTH

One of the characteristics of brittle materials is that they are stronger in compression than in tension. As stated in Section 4.1, the tensile strength of concrete is approximately 10% of its compressive strength. Brick, stone, and glass behave similarly. A ductile material such as steel has equal strength in compression and tension.

DUCTILITY AND FAILURE WARNING

Because its deformation at failure is small, a brittle material does not give any visual warning of its impending failure. Its failure is sudden. Failure of a ductile material, on the other hand, is gentle and is preceded by excessive deformation and ample warning. Structural safety concerns mandate ductile failure in building structures. Brittle failure is not permitted. Because concrete is a brittle material and steel is a ductile material, the use of steel reinforcement helps to impart a moderate amount of ductility to reinforced concrete members.

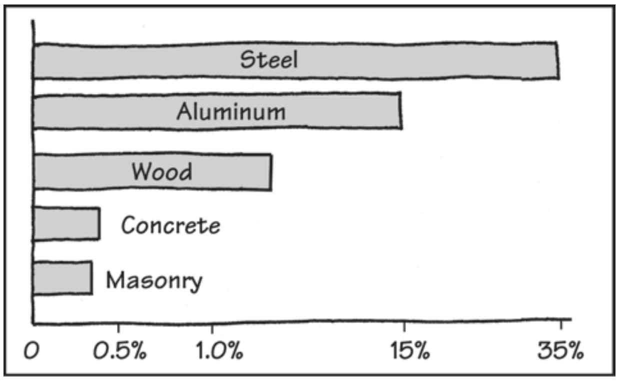


FIGURE 4.10 Approximate values of ultimate strain for selected materials (not to scale).

DUCTILITY AND MALLEABILITY

The terms *ductility* and *malleability* are used interchangeably in lay literature, although, strictly speaking, they represent different properties of materials. As stated previously, ductility is the property of a material to deform extensively prior to failure. Malleability, on the other hand, is the property that allows a material to be shaped by hammering, forging, pressing, and rolling. Ductile materials are generally malleable, but they need not be. For instance, cast iron is a ductile material (according to the definition of ductile material given earlier), but it cannot be converted into shapes by hammering or pressing. Cast-iron shapes are obtained by casting molten iron into molds.

PRACTICE **QUIZ**

Each question has only one correct answer. Select the choice that best answers the question.

1. The material in an arch is primarily in
   a. compression.
   b. tension.
   c. both tension and compression.
   d. shear.
   e. none of the above.

2. When a cable or rope is compressed by a force, what is the compressive stress in it?
   a. Equal to the force applied
   b. Force divided by the cross-sectional area of rope
   c. Zero
   d. Infinite
   e. None of the above

3. In a simple three-member truss consisting of two rafters and a tie, each member is in
   a. compression.
   b. tension.
   c. either tension or compression.
   d. shear.
   e. both tension and compression.

4. In a suspension bridge, which member(s) is (are) in compression?
   a. Suspension cable
   b. Hanger cables
   c. Support pylons
   d. Both suspension cable and hanger cables
   e. None of the above

5. A rectangular column measuring 12 in. × 12 in. in cross section carries a load of 18 kips. What is the stress in the column?
   a. 18 kips
   b. 18 ksi
   c. 2.25 ksi
   d. None of the above
   e. 125 psi

6. The test specimen used for determining the compressive strength of concrete in the United States is a
   a. cube measuring 12 in. × 12 in. × 12 in.
   b. cube measuring 6 in. × 6 in. × 6 in.
   c. prism measuring 6 in. × 6 in. × 12 in.
   d. cylinder measuring 12 in. in diameter × 6 in. high.
   e. cylinder measuring 6 in. in diameter × 12 in. high.

7. When we determine the strength of concrete using the test specimens, we determine the concrete's
   a. ultimate compressive stress.
   b. ultimate tensile stress.
   c. ultimate shear stress.
   d. modulus of elasticity.
   e. all of the above.

8. In relation to its compressive strength, the tensile strength of concrete is
   a. much higher.
   b. slightly higher.
   c. nearly the same.
   d. much lower.
   e. slightly lower.

9. A 20-ft-high column shortens by 0.6 in. under a load. What is the resulting strain in the column?
   a. 0.0020
   b. 0.0020 in.
   c. 0.0025 in.
   d. 0.0025
   e. None of the above

10. Which gives greater warning before failure?
   a. A brittle material
   b. A ductile material

4.3 YIELD STRENGTH OF MATERIALS

Because a load causes deformation, stress and strain occur simultaneously in a member. Generally, the strain increases as the stress increases. However, there are situations where stress may exist without strain or strain without stress. For example, a beam resting on two end supports will be subjected to a change in its length as the temperature of the beam increases or decreases. In this case, the strain occurs without any stress.

But if the same beam is clamped between the two end supports so that it cannot change its length, the beam will be subjected to stresses as its temperature changes—a case in which the stress occurs without the strain. The clamped beam will be subjected to compressive stress when its temperature rises and to tensile stress when its temperature falls.

The relationship between stress and strain conveys a great deal of information about the structural properties of the material and is unique to each material. This relationship is usually given in a graphical form, called the *stress-strain diagram*. In the stress-strain diagram, the stress is generally represented on the vertical axis and the strain on the horizontal axis.

The stress-strain diagram of one of the most important structural materials—low-carbon steel—is shown in Figure 4.11. The diagram is obtained by subjecting a round steel bar of standard length and diameter to an increasing tensile force. This is done in a tensile-testing machine (Figure 4.8), which is fully automated and gives the stress-strain diagram directly, thus avoiding the need to calculate stresses and strains and to plot them manually.

The diagram of Figure 4.11 begins at the origin (point O) because the strain must obviously be zero when the stress is zero—a no-load condition. It consists of three important points; Y, U, and F.

Point Y is called the *yield point*, and the stress corresponding to this point is called the *yield stress*. Yield stress is an important property of steel. A few types of steel are distinguished from each other by their yield stress values. For instance, A-36 steel is

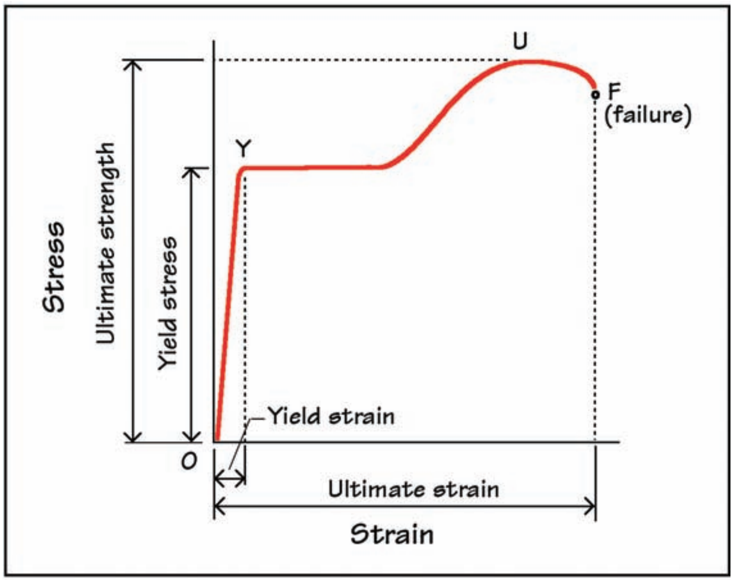


FIGURE 4.11 Stress-strain diagram for low-carbon (mild) steel in tension (not to scale).

so called because its yield stress is 36 ksi (the letter A in A 36 symbolizes a ferrous metal, per the specification of ASTM International). Steel used as reinforcing bars in concrete is called grade 40 or grade 60 steel, depending on whether its yield stress is 40 ksi or 60 ksi.

NOTE

Low-Carbon (Mild) Steel

Low-carbon steel is known as *mild steel* because of its higher ductility and the consequent ease with which it can be bent to shape and rolled into various cross-sectional shapes. High-strength steels are comparatively more brittle. They contain more carbon than mild steel. Therefore, they cannot be bent to shape or rolled into cross-sectional shapes with the same ease.

YIELD STRESS AND ULTIMATE STRENGTH

In the region OY of Figure 4.11, the relationship between stress and strain is a straight line, and the stress is proportional to the strain. Beyond point Y, the deformation in the bar increases substantially with little or no increase in the load, and the stress-strain diagram becomes (almost) horizontal. In other words, the steel yields after reaching point Y like a plastic material (such as modeling clay).

The yielding of steel produces a major rearrangement of the atoms in its crystalline structure, making steel stronger and harder, so the bar is able to sustain a greater load. This effect, referred to as *strain hardening*, is similar to that obtained by mechanical working on steel, such as cold rolling or hammering. We experience strain hardening when we take a piece of steel wire and bend it between our fingers. The wire becomes harder and stronger after bending, and it is more difficult to bend again at the original bend point.

Further increases in the load take the diagram of Figure 4.11 to point U, the point of maximum stress. The maximum stress is called the *ultimate stress*, or the *ultimate strength* of steel. Observe that the stress-strain diagram drops down between point U and the failure point F, indicating a loss of strength near failure. This is due to the manner in which the materials are tested and indicates the inability of testing equipment to keep the load on a rapidly disintegrating material.

Although point U represents the ultimate strength of steel, for all practical purposes it is the yield stress that is considered as the limiting stress in steel. Because steel deforms excessively after yield and because excessive deformation is to be avoided in a structure, we limit the actual stress in steel members to remain well below the yield stress. Therefore, although not absolutely correct, yield stress is also referred to as the *yield strength* of steel.

The yielding of the material is not peculiar to steel. It occurs in several metals and is an extremely useful property, because it provides ductility. Additionally, the strain hardening that follows yield makes the metal stronger.

4.4 ELASTICITY AND PLASTICITY

A material is called an *elastic material* if it is fully recoverable from deformation after the load is removed. The property responsible for the elastic behavior of the material is called *elasticity.* The converse of elasticity is called *plasticity.* Thus, a material that does not recover from its deformation after the removal of the load is called an *inelastic,* or *plastic, material.* Materials are generally elastic only up to a small strain value—approximately 0.5%. As stated earlier, the ultimate strain in brittle materials such as concrete, brick, stone, and glass is of this order (0.5%). Therefore, brittle materials are generally elastic up to failure.

Metals, on the other hand, can sustain large deformations, usually greater than 10%. They are elastic up to a certain stress level, and if loaded beyond that stress value, they are plastic—that is, their deformation beyond that point is permanent. For example, steel is elastic up to the yield point (between points O and Y in Figure 4.11) but plastic thereafter. In other words, if the stress in a steel member remains below the yield stress, the member is fully recovered from any deformation after the load is removed. Materials that are elastic up to a certain stress value and plastic thereafter are called *elastic-plastic materials.* Thus, low-carbon steel is an elastic-plastic material. The same applies to aluminum—another important metal used in buildings, generally in windows and glass curtain walls.

Building structures are designed so that the stresses in materials remain within the elastic limit and so that no inelastic deformations occur under design loads. Because they are permanent, inelastic deformations affect the appearance of structures. The exception to this general philosophy is made in the design of structures located in highly seismic areas. The maximum intensity of earthquake loads in such areas is so high that if structures were designed to remain elastic, member sizes (columns, beams, and floor slabs) would have to be so large as to make the structure highly uneconomical.

Thus, as stated in Section 3.9, the structural design philosophy for buildings located in seismic zones is that the building components should deform elastically under low to moderately intense earthquakes so that after the earthquake event, the building regains its original shape and size. However, under severe earthquake loads, the structure is designed to deform inelastically (plastically) without compromising its safety or integrity. The structure may become unusable and unserviceable because of plastic deformations but will remain integral to provide life safety.

4.5 MODULUS OF ELASTICITY

The ratio of stress to strain in a material is called the *modulus of elasticity*. Thus,

$$\boxed{\frac{\text{Stress}}{\text{Strain}} = \text{E}} \qquad \textbf{Eq. (4.3)}$$

where E denotes the modulus of elasticity. A measure of the material's stiffness, the modulus of elasticity is a property of the material. The larger the value of E, the stiffer the material and the less it will deform under a given load.

On the stress-strain diagram, the value of E is represented by the slope of the diagram. The greater the slope, the larger the value of E and, hence, the stiffer the material. Thus, in Figure 4.12, the value of E is larger for Material 1 than for Material 2. For a *rigid* material, the value of E would be infinite. This is obvious from Equation (4.3), because for a rigid material, the strain is zero regardless of the value of stress. Therefore, the stress-strain diagram for a rigid material is a vertical line because on a vertical line, the strain is zero.

The concept of the modulus of elasticity as a material property (constant for a material) assumes a linear stress-strain diagram. If the stress-strain diagram is a curve, the modulus of elasticity is not constant but varies with the stress level. Most construction materials fall into this category, that is, they do not have a linear stress-strain diagram. The exception is steel, which has a linear stress-strain diagram only up to the yield point. Because yield stress is, practically, the limiting stress in steel, steel may be considered as having a linear stress-strain diagram for all practical purposes.

The modulus of elasticity of a material that does not have a linear stress-strain diagram is obtained from the straight line whose slope is approximately equal to the slope of the initial part of its stress-strain diagram. This approximation is justified on the basis that in actual buildings, the materials are usually loaded to low or moderate stress levels so that the slope of the initial part of the diagram is a good approximation to the modulus of elasticity of the material.

Figure 4.13 shows the stress-strain diagram for concrete. Because the diagram is nonlinear, the modulus of elasticity is given by the slope of the straight line OA, where A represents 40% of the compressive strength of concrete. Thus, if the strength of concrete is 4,000 psi, point A represents a stress level of 1,600 psi.

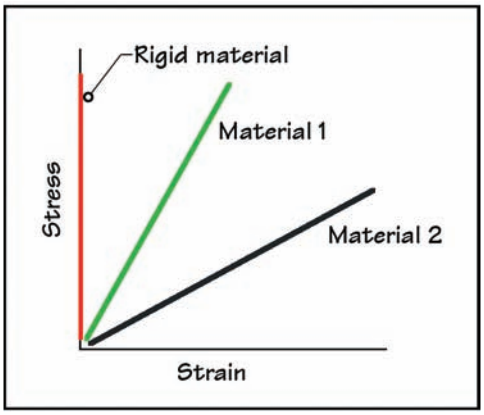


FIGURE 4.12 The slope of a material's stress-strain diagram gives the magnitude of the modulus of elasticity of the material, E. The greater the slope, the greater the value of E. Thus, in this illustration, Material 2 has the lowest value of E.

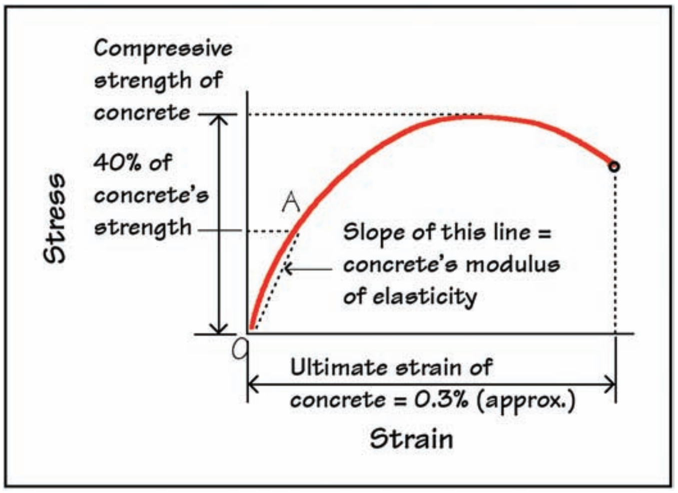


FIGURE 4.13 Stress-strain diagram of concrete.

UNITS OF MODULUS OF ELASTICITY

From Equation (4.3), the unit of the modulus of elasticity is the same as that of stress, because strain has no units. In other words, the unit of E is psi or ksi (pascal in the SI system). The E value of materials is usually a large number—millions of pounds per square inch (gigapascals in the SI system, where 1 GPa $= 10^9$ Pa).

For a soft rubber, the value of E is a relatively small number. Of the commonly used materials, diamond has the highest value of E (greatest stiffness). That is why diamond-tipped tools are used to cut window glass, masonry, and concrete. Table 4.1 gives the modulus of elasticity values of a few selected materials.

MODULUS OF ELASTICITY AND STRENGTH OF MATERIALS

Being a measure of the stiffness of the material, modulus of elasticity determines how much a material will deform under loads. Because deformation control is a structural design criterion, modulus of elasticity is an important material property. It determines how much a beam or slab will deflect under a given load or how much a tall building will sway sideways under the action of wind.

NOTE

Artificial Diamond

The diamond commonly used on the tips of cutting tools, such as saw blades and glass-cutting wheels, is artificial. Artificial diamond, first patented by Edward Acheson in 1926, was carborundum—a trade name for silicon carbide—made from clay and carbon. Since then, several other metal carbides, such as tungsten carbide and titanium carbide, have been produced. Pure diamond is 100% crystalline carbon.

TABLE 4.1 MODULUS OF ELASTICITY OF SELECTED MATERIALS

Material	Modulus of elasticity ($\times 10^6$ psi)
Wood	1.0–2.0
Brick masonry	1.0–3.0
Concrete	3.0–8.0
Steel	29.0
Aluminum alloys	10.5
Window glass	10.4
Diamond	170
Rubber	0.001

For most materials, the modulus of elasticity increases with the strength of the material. Higher-strength species of wood, for example, have higher moduli of elasticity than lower-strength species. The same is true of concrete and masonry. The greater the concrete strength, the greater is its modulus of elasticity. However, steel has the same modulus of elasticity regardless of its strength. In other words, high-strength steels have the same modulus of elasticity as low-carbon (mild) steel.

Steel is the stiffest of all construction materials; that is, it has the highest value of E (29×10^6 psi). Its modulus of elasticity is based on the straight-line portion of the stress-strain diagram, points O to Y in Figure 4.11. Because, unlike other materials, the modulus of elasticity of steel does not increase with strength, high-strength steel is not as commonly used in structural steel sections as low-carbon (mild) steels.

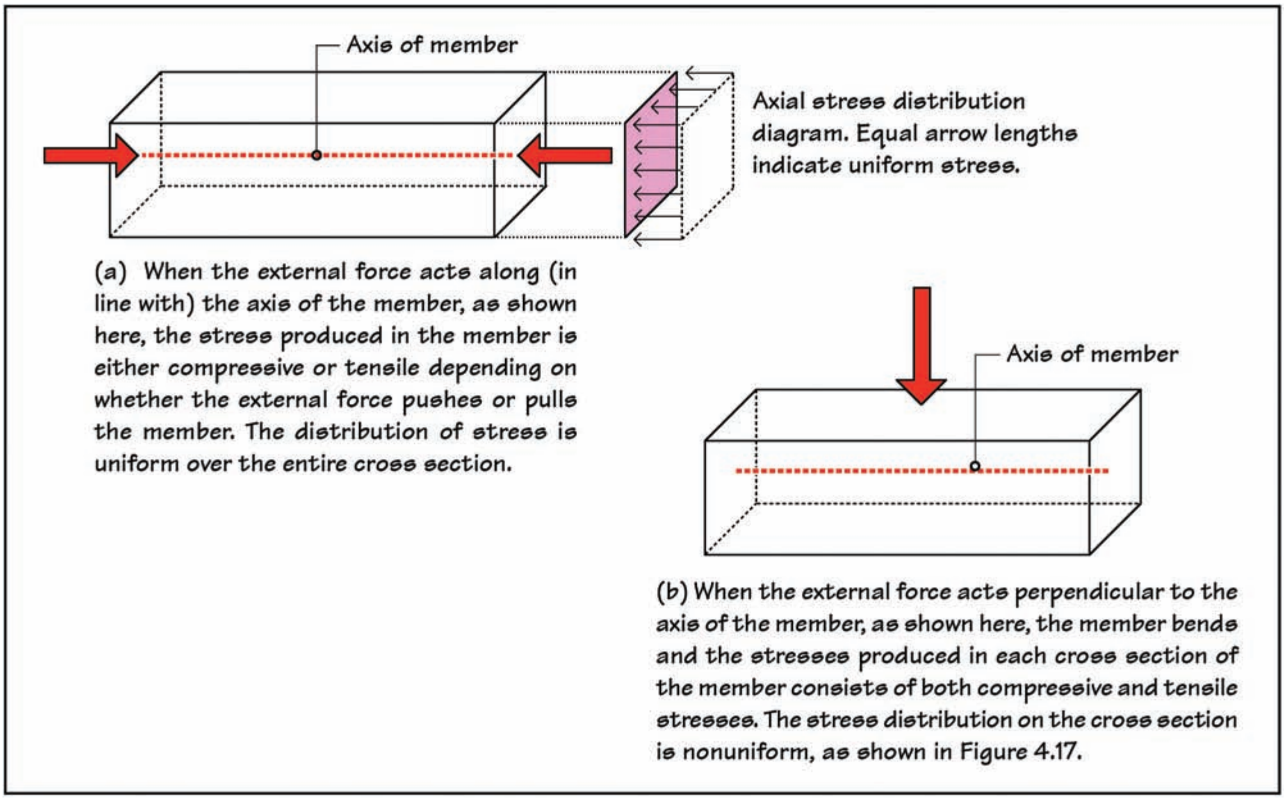
4.6 BENDING STRENGTH OF MATERIALS

So far, we have discussed situations in which either tensile or compressive stress is present in a member. For example, in the suspension bridge of Figure 4.5, the pylons are in compression and the cables and hanger bars are in tension. In such cases, the external force acts along the axis of the member, as shown in Figure 4.14(a). The presence of the axial force may be obvious, as in Figure 4.5, or not directly obvious, as in the rafter-joist assembly of Figure 4.4(b).

Because the external force is axial, the stress created in the member is referred to as an *axial stress*. The axial stress is uniform over the entire cross section, as shown in Figure 4.14(a), and may be either compressive or tensile. However, if the external force acts perpendicular to the axis of a member, as seen in Figure 4.14(b), the member bends, subjecting itself to both compressive and tensile stresses simultaneously.

A force acting in a downward direction on a beam that is supported at the ends bends it with a concave *water-holding curvature*, like the inside of a saucer. An upward-acting force will cause it to have a convex *water-shedding curvature*, like the outside of a sphere. Bending (also called *flexure)* is a predominant action in building structures. Gravity loads produce bending in beams and slabs, and lateral loads cause bending in walls and columns.

Bending produces compression in one-half of a member's cross section and tension in the other half. This can be demonstrated by bending a member made of a soft material such as rubber or sponge. If we mark two vertical lines, PQ and RS, on one of the longitudinal faces of a sponge beam and bend it to produce a concave curvature, as shown in Figure 4.15, we

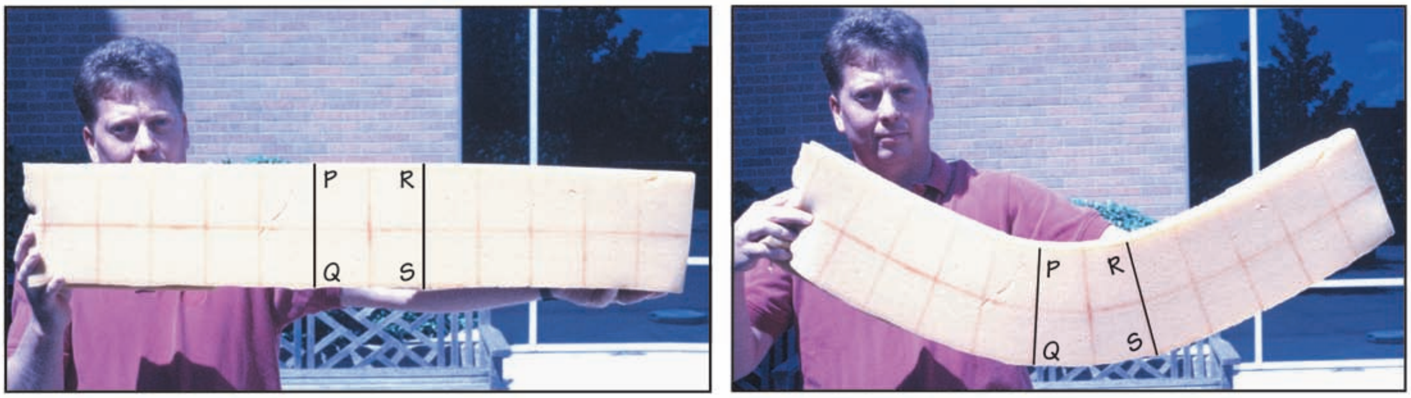


Axial stress distribution diagram. Equal arrow lengths indicate uniform stress.

(a) When the external force acts along (in line with) the axis of the member, as shown here, the stress produced in the member is either compressive or tensile depending on whether the external force pushes or pulls the member. The distribution of stress is uniform over the entire cross section.

(b) When the external force acts perpendicular to the axis of the member, as shown here, the member bends and the stresses produced in each cross section of the member consists of both compressive and tensile stresses. The stress distribution on the cross section is nonuniform, as shown in Figure 4.17.

FIGURE 4.14 The orientation of the external force with respect to the axis of the member and the types of stress produced in the member.



(a) Beam before bending

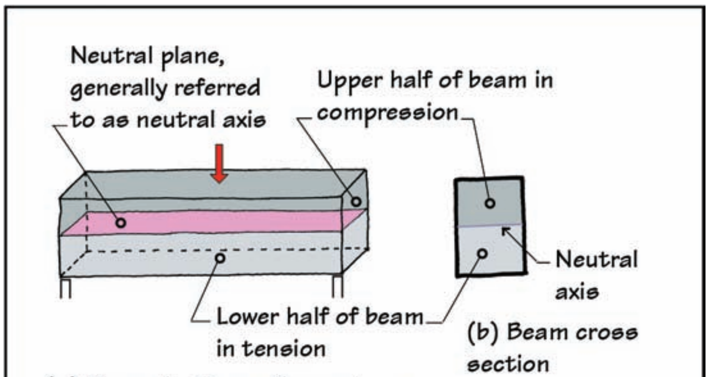
(b) Beam after bending

FIGURE 4.15 Demonstration of bending in a beam. In a beam bent with a water-holding curvature, as shown in **(b)**, the upper half of the beam is in compression and the lower half of the beam is in tension.

see that the lines have become closer at the top and farther apart at the bottom. Fibers of the beam represented by line PR have become shorter in length, and fibers on the line QS have become longer.

Further examination of the deformed shape of rectangle PQSR shows that maximum contraction takes place along line PR, the extreme top surface of the beam. The maximum elongation is produced along the line QS, the extreme bottom surface of the beam. In other words, compressive stresses are maximum at the top surface, and tensile stresses are maximum at the bottom surface of the beam.

The change from compressive to tensile stresses occurs on the surface that neither contracts nor stretches; that is, this surface maintains its original dimension and is, therefore, unstressed. This surface is the neutral plane, commonly referred to as the *neutral axis* of the beam, Figure 4.16. Thus, the neutral axis is a line on the beam's cross section where the stresses are zero.


Neutral plane, generally referred to as neutral axis
Upper half of beam in compression
Lower half of beam in tension
Neutral axis

(a) Beam in three dimensions

(b) Beam cross section

FIGURE 4.16 The location of neutral axis in a beam under bending stresses. Note that the neutral axis is, in fact, a neutral plane. It is called neutral axis because we generally draw a beam in two dimensions—in cross section—in which the neutral plane shows as a line.

IMPROVING THE BENDING STRENGTH OF MEMBERS

If we isolate a small length of the beam, such as length PQSR in Figure 4.15, and examine the distribution of stresses on cross sections represented by lines PQ and RS, we see that the distribution is as shown in Figure 4.17. The term *bending stress* (or *flexural stress*) is used to describe this distribution of stresses—compressive stresses on one side of the neutral axis and tensile stresses on the other side.

The stress distribution shown in Figure 4.17 represents stresses in the beam when it bends with a water-holding curvature. If the beam bends with a water-shedding curvature,

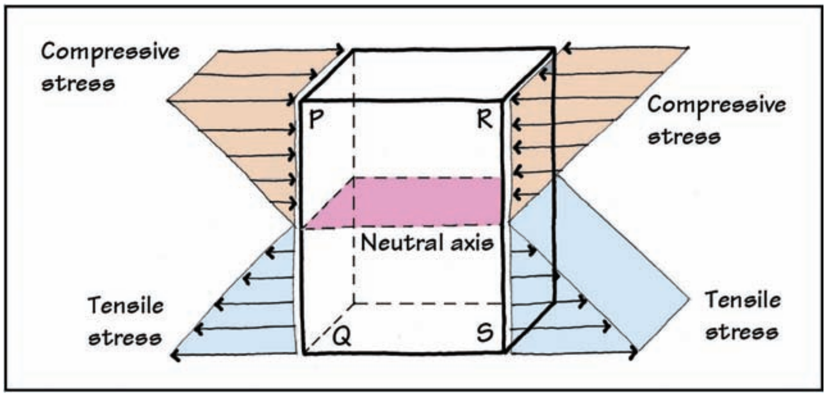


FIGURE 4.17 Stress distribution on a small length, PQSR, of the beam of Figure 4.15.

the stresses will simply be reversed; that is, tensile stresses will be created in the upper half of the beam and compressive stresses in the lower half of the beam.

Stresses are unequally distributed throughout the beam's cross section in bending. They are concentrated at the top and bottom of the cross section, but the central part of the cross section is relatively stress free—an inefficient use of the material. By contrast, the axial stress distribution is uniform over the entire cross section, as shown in Figure 4.14(a). Thus, structural configurations that generate axial stresses in members use the material efficiently.

In suspension structures, where members are either in compression or in tension (Figure 4.5), loads are carried very efficiently. That is why suspension structures are popular for long-span structures such as bridges.

Architects and engineers have overcome the structural inefficiency in bending by developing the I-shaped cross section. This configuration places most material at the top and bottom of the beam where stresses are greatest, thus making it more efficient than a (solid) rectangular section. I-shaped beams in steel, wood, and concrete are commonly used in buildings and civil engineering structures, Figure 4.18.

Some of the other strategies used in response to the structural inefficiency in bending are tubular cross sections, hollow-core concrete slabs, and open-web-steel I-shaped beams, Figure 4.19.

NOTE

Structural Efficiency

A structurally efficient shape is one that can withstand a greater load for the same amount of material. For example, a beam with an I-section (Figure 4.18) is structurally more efficient because it can withstand a greater load than a rectangular beam of the same cross-sectional area and span. A hollow-core concrete slab (Figure 4.19(b)) is structurally more efficient than a solid slab with the same amount of material.

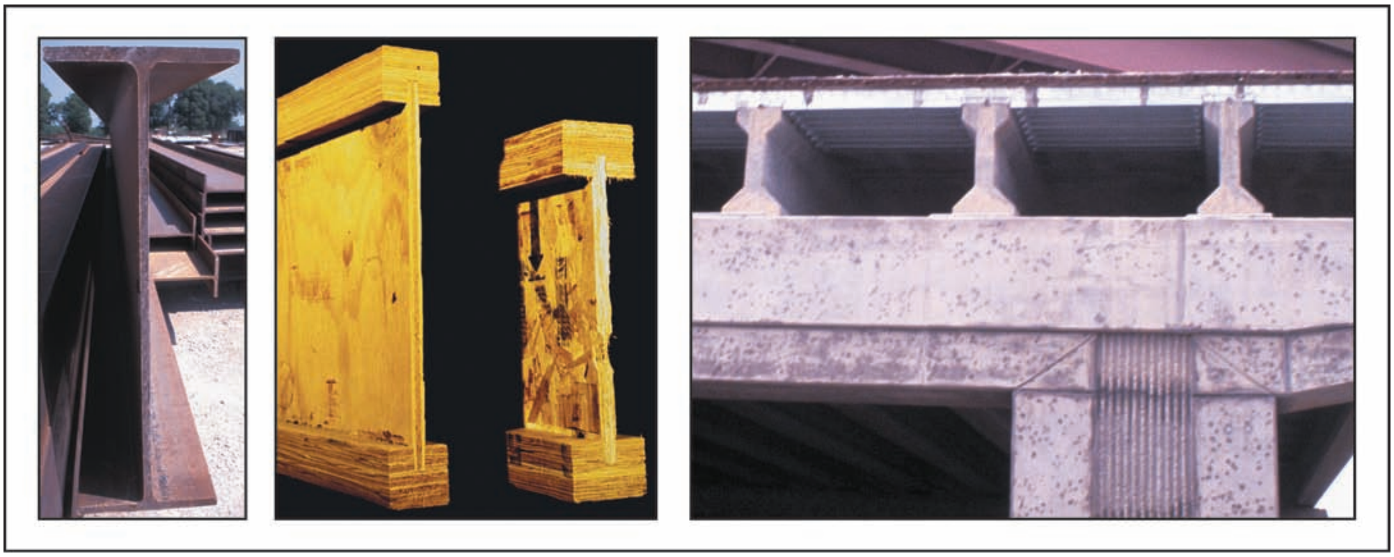
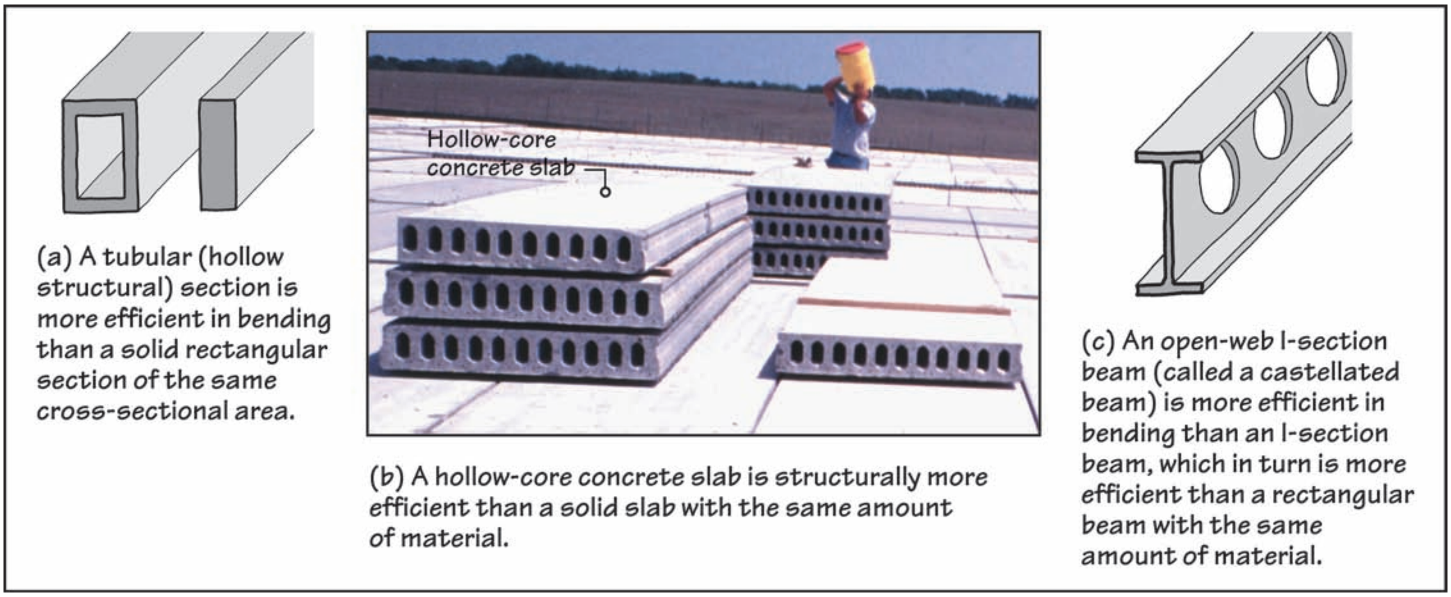


FIGURE 4.18 I-section beams are commonly used in steel, wood, and concrete.



(a) A tubular (hollow structural) section is more efficient in bending than a solid rectangular section of the same cross-sectional area.

(b) A hollow-core concrete slab is structurally more efficient than a solid slab with the same amount of material.

(c) An open-web I-section beam (called a castellated beam) is more efficient in bending than an I-section beam, which in turn is more efficient than a rectangular beam with the same amount of material.

FIGURE 4.19 Some strategies used to improve the structural efficiency of members subjected to bending. The structural efficiency of a member subjected to bending improves by removing the material from the central region of the cross section (where the stresses are low) and placing it closer to the extremes edges of the cross section (where the stresses are high).

BENDING STRENGTH OF BRITTLE MATERIALS IS LOW

Because bending creates tensile as well as compressive stresses, brittle materials, being weak in tension, are also weak in bending. Ductile materials, such as steel, which have equal strengths in tension and compression, have a higher bending strength. Reinforced concrete is a composite material that exploits the moderately high compressive strength of concrete and the high tensile strength of steel.

Steel is placed in those locations of a reinforced concrete member where tensile stresses are present. For instance, in a beam supported at two ends, tensile stresses occur in the lower half of the beam's cross section. Therefore, steel reinforcing bars are placed along the length of the beam at the bottom of the beam's cross section, Figure 4.20. (Also see Section 22.5 for additional details.)

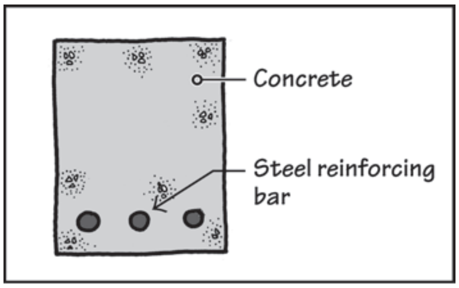


FIGURE 4.20 Section through a typical reinforced concrete beam. Note that steel reinforcing bars are used in the region of the cross section that is subjected to tension.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

11. In a typical stress-strain diagram of a material, the stress is generally plotted along the vertical axis.
- **a.** True
- **b.** False

12. What is the yield stress of grade 60 reinforcing steel?
- **a.** 60 lb
- **b.** 6,000 lb
- **c.** 6,000 psi
- **d.** 60 psi
- **e.** None of the above

13. The stress-strain diagram of mild steel is nearly a straight line up to the yield point.
- **a.** True
- **b.** False

14. Low-carbon (mild) steel is
- **a.** an elastic material.
- **b.** a plastic material.
- **c.** an elastic-plastic material.
- **d.** none of the above.

15. Concrete is
- **a.** an elastic material.
- **b.** a plastic material.
- **c.** an elastic-plastic material.
- **d.** none of the above.

16. Modulus of elasticity refers to how
- **a.** strong a material is.
- **b.** stiff a material is.
- **c.** elastic a material is.
- **d.** serviceable a material is.
- **e.** none of the above.

17. The unit of modulus of elasticity is
- **a.** psi.
- **b.** ksi.
- **c.** Pa.
- **d.** GPa.
- **e.** all of the above.

18. The bending stresses along the neutral axis of a beam are
- **a.** minimum.
- **b.** maximum.
- **c.** zero.
- **d.** none of the above.

19. Which of the following beam cross sections is structurally more efficient in bending?
- **a.** Rectangular (solid) section
- **b.** I-section

20. Which of the following beam cross sections is structurally more efficient in bending?
- **a.** Rectangular (solid) section
- **b.** Tubular section

4.7 SHEAR STRENGTH OF MATERIALS

So far, we have discussed the strength of materials under axial stress and bending stress. Both of these stresses—axial stress (which can be compressive or tensile) and bending stress (a combination of compressive and tensile stresses)—are *normal stresses*, implying that the stress acts perpendicular (normal) to the cross section of the member (see Figures 4.14(a) and 4.17). A second type of stress, called *shear stress,* acts tangential to the cross section of the member. In fact, normal stress and shear stress are the only two basic types of stress. Various types of stress that exist in a member belong to either normal stress or shear stress, Figure 4.21.

Shear stress is caused by a force that is tangential to the cross section of the member. Because it is tangential, a shear force tends to produce a sliding effect on the body. Shear stress is, therefore, associated with the resistance of the layers within the body to sliding over each other, Figure 4.22. Like normal stress, shear stress is also defined as the shear force divided by the area and has the same units as normal stress—psi or ksi.

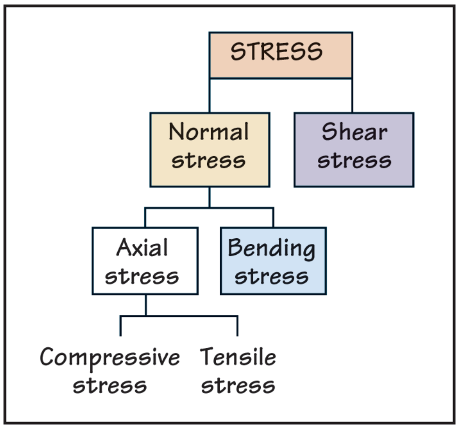


FIGURE 4.21 Types of stresses that may exist in a structural member.

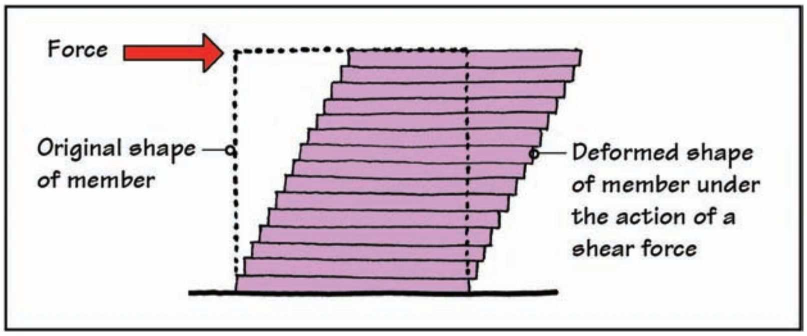


FIGURE 4.22 The deformation caused by a shear (tangential) force on a member.

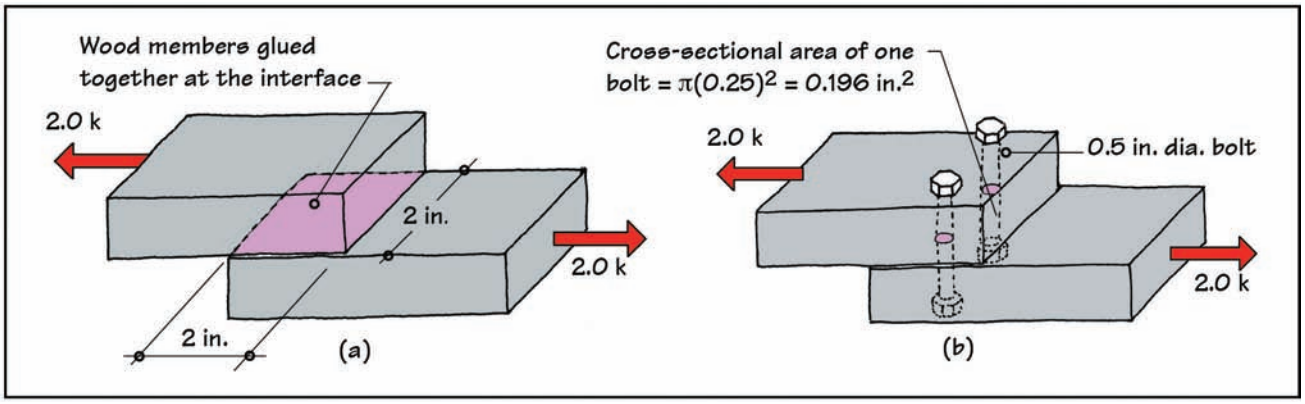

Wood members glued together at the interface
2.0 k
2 in.
2.0 k
2 in.
(a)
Cross-sectional area of one bolt = π(0.25)² = 0.196 in.²
2.0 k
0.5 in. dia. bolt
2.0 k
(b)

FIGURE 4.23 The magnitude of shear stress equals the shear force divided by the area that resists the shear force (sliding action).

Consider an assembly of two wood members glued together at the interface, as shown in Figure 4.23(a). If a force pulls on the assembly, axial tension is developed in each member. In addition to the axial stress, the assembly develops shear stress to resist sliding at the interface. The interface area of the assembly that resists shear has been colored. For example, if this area is 2.0 in. by 2.0 in. (4.0 in.^{2}) and if the force acting on the assembly is 2.0 kips, then the shear stress developed at the interface is

$$\text{Shear stress} = \frac{\text{force}}{\text{area}} = \frac{2.0}{4.0} = 0.5 \text{ ksi} = 500 \text{ psi}$$

If the members are joined together with bolts, as shown in Figure 4.23(b), instead of being glued together at the interface, the shear force will now be resisted by the cross-sectional area of the bolts. For example, if there are two 0.5-in.-diameter bolts, the shear stress in bolts is

$$\text{Shear stress} = \frac{2.0}{2(0.196)} = 5.1 \text{ ksi}$$

LOW SHEAR STRENGTH OF BRITTLE MATERIALS

As shown in Figure 4.22, a shear force causes an angular deformation in an element, changing the element's shape, not its dimensions. Thus, a rectangular element becomes an oblique element. This introduces tension along one diagonal of the member and compression along the other, Figure 4.24. Because of the tension created by shear, brittle materials—which are weak in tension—are also weak in shear. Steel, on the other hand, has a fairly high shear strength, because it has the same (high) strength in tension as well as compression.

In the concrete beam illustrated in Figure 4.20, the longitudinal steel reinforcement placed at the bottom of the beam is adequate to resist tensile stresses resulting from bending, but additional steel is required to resist shear. Steel stirrups are therefore used in concrete beams to resist shear stresses, Figure 4.25. (See Section 22.5 for additional details.)

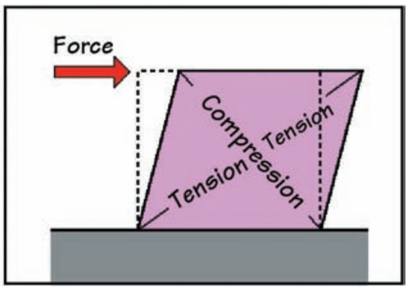


FIGURE 4.24 The deformation caused by a shear force on a member illustrates that shear stress is a combination of tensile stress along one diagonal and compressive stress along the other diagonal of the member.

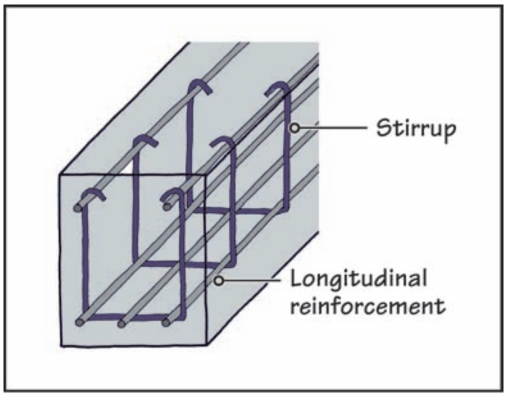


FIGURE 4.25 Steel stirrups in a reinforced concrete beam are used to increase the beam's shear strength.

4.8 BEARING STRENGTH OF MATERIALS

When we speak of the compressive strength of a material, we imply that a specimen of the material was tested to failure without any confinement in the lateral direction; that is, the test specimen was allowed to expand freely in the direction perpendicular to the load. This is how we determine the compressive strength of concrete in a standard compression test. As the cylinder is loaded to failure from the vertical direction, it is free to bulge out horizontally (see Figure 4.6).

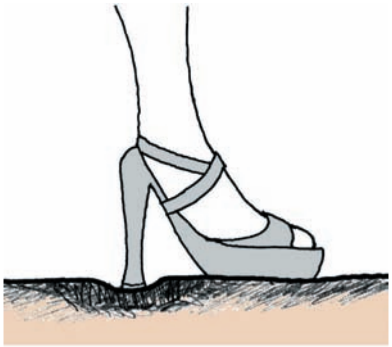
However, if a cylinder is tested with horizontal confining stress throughout its entire height, as shown in Figure 4.26, we observe that the cylinder fails at a higher load than an unconfined cylinder made from the same concrete. For example, assume that a concrete cylinder under the standard compression test (no lateral confinement) tests to a compressive strength of 3,500 psi. If we prepare another cylinder from the same batch of concrete and impose a lateral confining stress of 1,000 psi during the compression test, we find that the cylinder tests to a compressive strength of nearly 9,000 psi. When the lateral confinement is increased to 2,000 psi, a cylinder from the same batch of concrete tests to a compressive strength of nearly 13,000 psi, Figure 4.27.

Confining compressive stress exists in deep and thick columns and walls. In such elements, the material in the interior portions is not free to expand laterally because of the confining effect of the exterior mass. Consequently, the interior material posts a higher compressive strength than the material on the exterior of such elements.

This fact is also used in the design of a column footing. The concrete footing generally has a much larger area than the cross-sectional area of the column. Therefore, as the column delivers the load to the footing, the concrete immediately under the column experiences the confining effect of the mass of the concrete surrounding the column base. Thus, the concrete in the footing exhibits greater overall compressive strength than that obtained from the standard compression test. This state of compressive stress, created at the surface of contact between the column and the footing, is referred to as the *bearing stress,* and the corresponding strength of the material is called the *bearing strength* of the material.

In general, when one element delivers a compressive load on the supporting element, the surface area of contact between the two elements is called the *bearing area.* If the bearing area is larger than the area of the supporting surface, a confining effect occurs, and the stress created in the bearing area is referred to as the *bearing stress.* Therefore, bearing stress is the (compressive) load divided by the bearing area (contact area) between the two elements.

Bearing failure occurs when the load causes the bearing stress in the material to exceed its bearing strength. Usually, bearing failure does not result in complete crushing of the material but rather partial crushing, or what is referred to as *local crushing.* Local crushing in a structural member is similar to the crushing (or settlement) of ground directly under the pointed heel of a shoe.



Local crushing or settlement (bearing failure)

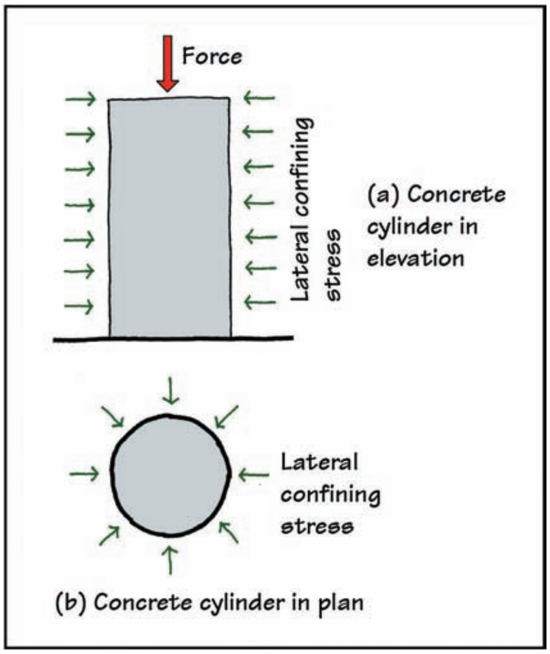

Force
Lateral confining stress
(a) Concrete cylinder in elevation
Lateral confining stress
(b) Concrete cylinder in plan

FIGURE 4.26 A concrete cylinder (shown in plan and elevation) tested to failure under lateral confinement.

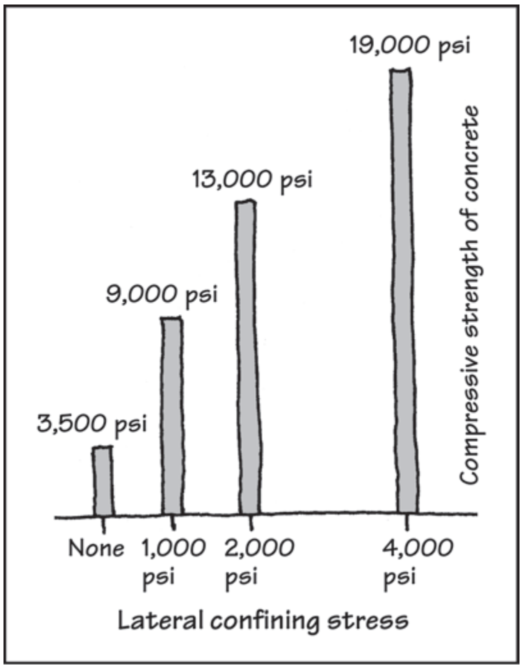


FIGURE 4.27 The effect of lateral confinement on the compressive (crushing) strength of concrete. The compressive strength of (a given batch of) concrete increases as the confining stress on it is increased.

BEARING PLATES

In building structures, a steel plate is generally used to prevent bearing failure (local crushing) that could occur when one element delivers a concentrated compressive load to another element. For example, if a wide-flange steel column is placed directly on a concrete footing, a bearing failure (local crushing) in the concrete could result, because concrete's bearing strength is much lower than the compressive stress in the steel column.

The provision of a steel plate, with a larger surface area, at the base of the column distributes the column load over a larger area, reducing the stress on the concrete. Because the column bears on the steel plate, the steel plate is referred to as the *bearing plate,* Figure 4.28. For the same reasons, a bearing plate is also used when a steel beam rests on a concrete column or wall, Figure 4.29.

Referring to Figure 4.28 again, the column is said to "bear" on the bearing plate; the bearing plate "bears" on the concrete footing, and the footing "bears" on the soil below. The bearing stress of the materials must be checked at each interface to ensure that it does not exceed the bearing strength of the material.

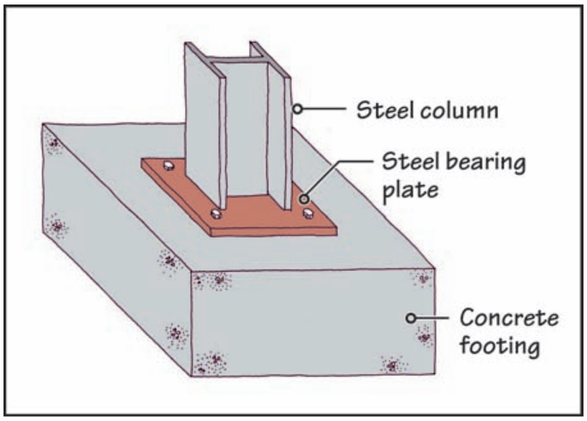


FIGURE 4.28 Bearing plate under a steel column. In this illustration, the column is said to "bear" on the bearing plate. The bearing plate is said to "bear" on the footing, and the footing is said to "bear" on the soil.

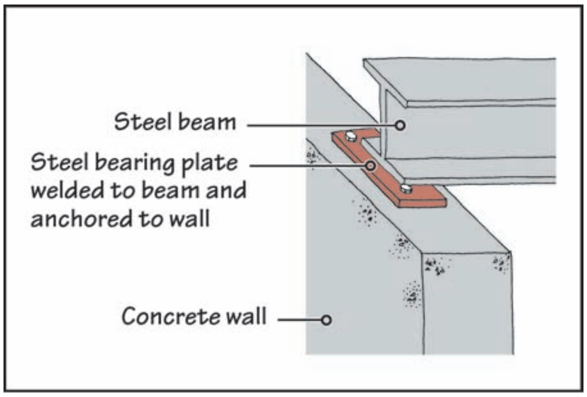


FIGURE 4.29 Bearing plate under a steel beam.

BEARING CAPACITY OF SOIL

Because the soil directly under a footing is confined by a large mass of the surrounding ground, the compressive strength of the soil is referred to as the *bearing strength* or, more commonly, as the bearing capacity of the soil (see Section 11.4). Observe that the *bearing strength* of a material is essentially its compressive strength plus the effect of confinement, when present. If there is no confinement, the bearing strength of the material is the same as the compressive strength of the material.

4.9 STRUCTURAL FAILURES

The structural failure of a member can occur in several ways, depending on the type of stress in the member. Because stresses in a member can either be compressive, tensile, or a combination of tensile and compressive stresses, compressive and tensile failures are the two basic types of structural failure.

COMPRESSIVE AND TENSILE FAILURES

A compressive failure is sudden and catastrophic, Figure 4.30. A tensile failure (particularly of a ductile material) is preceded by necking and elongation of the member, giving sufficient warning of the failure, Figure 4.31.

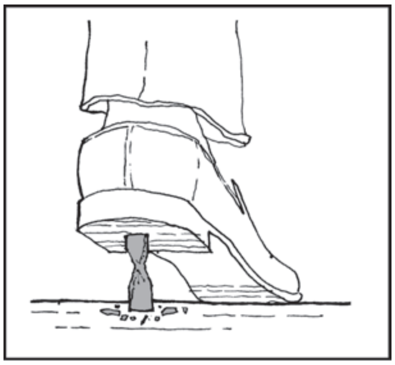


FIGURE 4.30 Failure mode of a member under axial compression (compressive failure). This mode of failure occurs in a short, squat member made of brittle material such as concrete, brick, or stone. Compressive failure is abrupt.

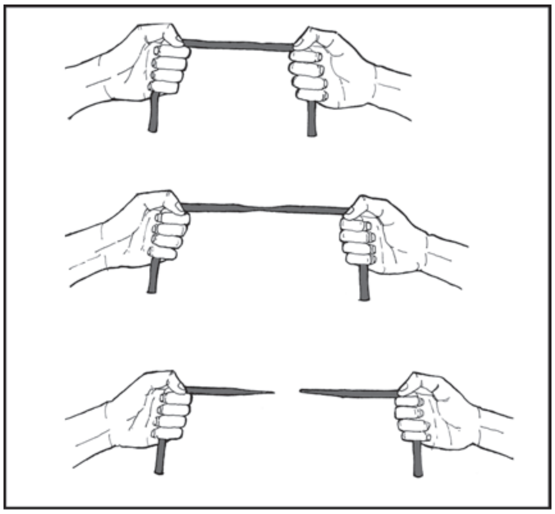


FIGURE 4.31 Failure of a member in tension—tensile failure. If the member is made of a ductile material, such as steel or aluminum, tensile failure is gradual and is generally preceded by "necking" of the member, and hence a large deformation.

BENDING FAILURE

Bending (stress) failure may either be sudden or gradual, depending on whether the member fails in compression or tension. The same applies to shear failure, because, like bending stress, shear stress is also a combination of compressive and tensile stresses.

BUCKLING FAILURE

A type of failure that is entirely different from the failures just described is buckling failure. Buckling failure occurs in a long, slender member subjected to axial compressive stress. (A slender member is one whose length is much greater than its cross-sectional dimensions.) Although a short, squat member will fail by the crushing of the material (as shown in Figure 4.30), a long, slender member will bend under an axial compressive load. The bending of a member under an axial compressive load is called *buckling.*

Buckling is similar to bending. The difference between bending and buckling is that bending is produced by loads that are perpendicular to the axis of the member and buckling is caused by axial loads. A more significant difference between the two, however, is that the bending of a member takes place under all magnitudes of loads, however small. Buckling occurs when the load increases to a certain critical value, called the *critical load.*

Therefore, unlike bending, buckling takes place abruptly. The buckling of a member is recognized as one of the failure mechanisms, although it usually does not lead to a complete collapse of the structure. By buckling under the load, the member becomes unstable but will generally not fracture. In some situations, however, the instability caused by buckling in one member may lead to excessive stresses in other members, thereby causing a progressive collapse of the structure.

Buckling can be easily demonstrated by taking a plastic ruler and subjecting it to increasing axial compression. The more slender the ruler, the smaller the compressive force needed to produce a buckling failure in it, Figure 4.32.

Buckling is an important consideration in the design of columns and load-bearing walls. Steel columns are more prone to buckling than concrete columns because they are more slender. Even slender beams and floor joists are prone to buckling because of the presence of compressive stresses resulting from their bending. Remember, bending is a combination of tensile and compressive stresses.

To strengthen a member against buckling failure, we can either reduce its slenderness—that is, increase its cross-sectional dimension—or brace it at intermediate point(s) along its length or height. Usually, the latter approach (bracing the member) is used, because increasing the cross-sectional dimension is uneconomical. For instance, studs in a wood light frame wall must be solidly blocked if it is determined that they may buckle under loads, Figure 4.33. Slender beams and joists require similar bracing, Figure 4.34, because compression is produced in their top fibers as they bend. This compression may cause the slender beams and joists to buckle sideways, a phenomenon known as *lateral buckling.*

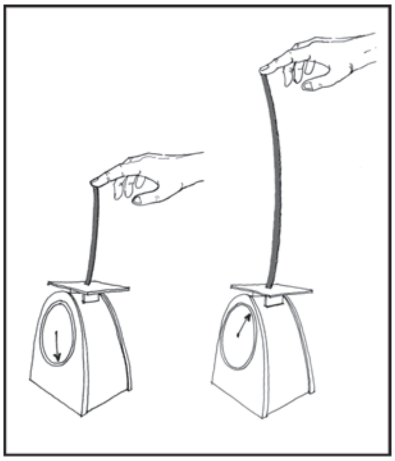


FIGURE 4.32 Buckling of a slender member. The more slender the member, the smaller is its buckling load.

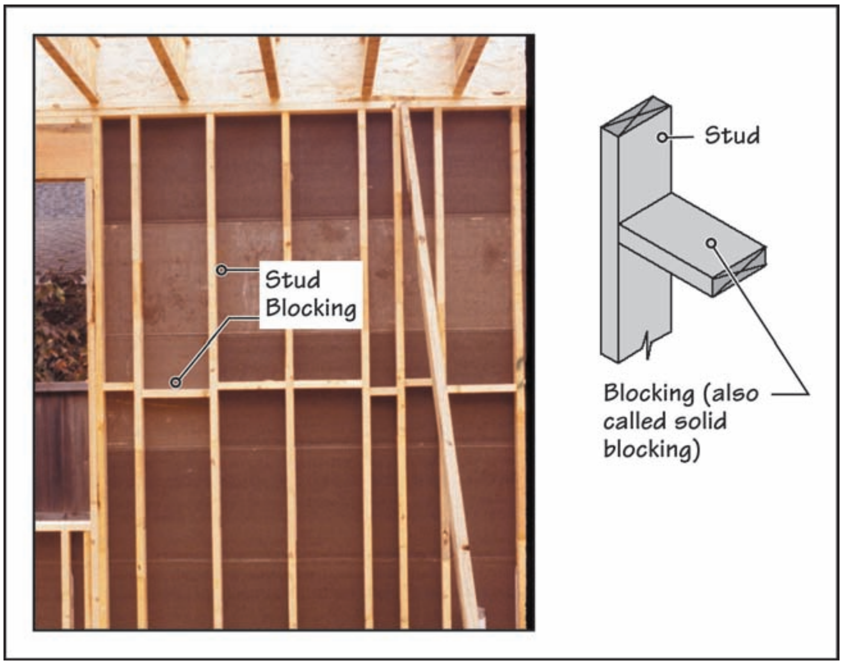


FIGURE 4.33 Solid blocking in a wood frame wall to prevent the buckling of studs.

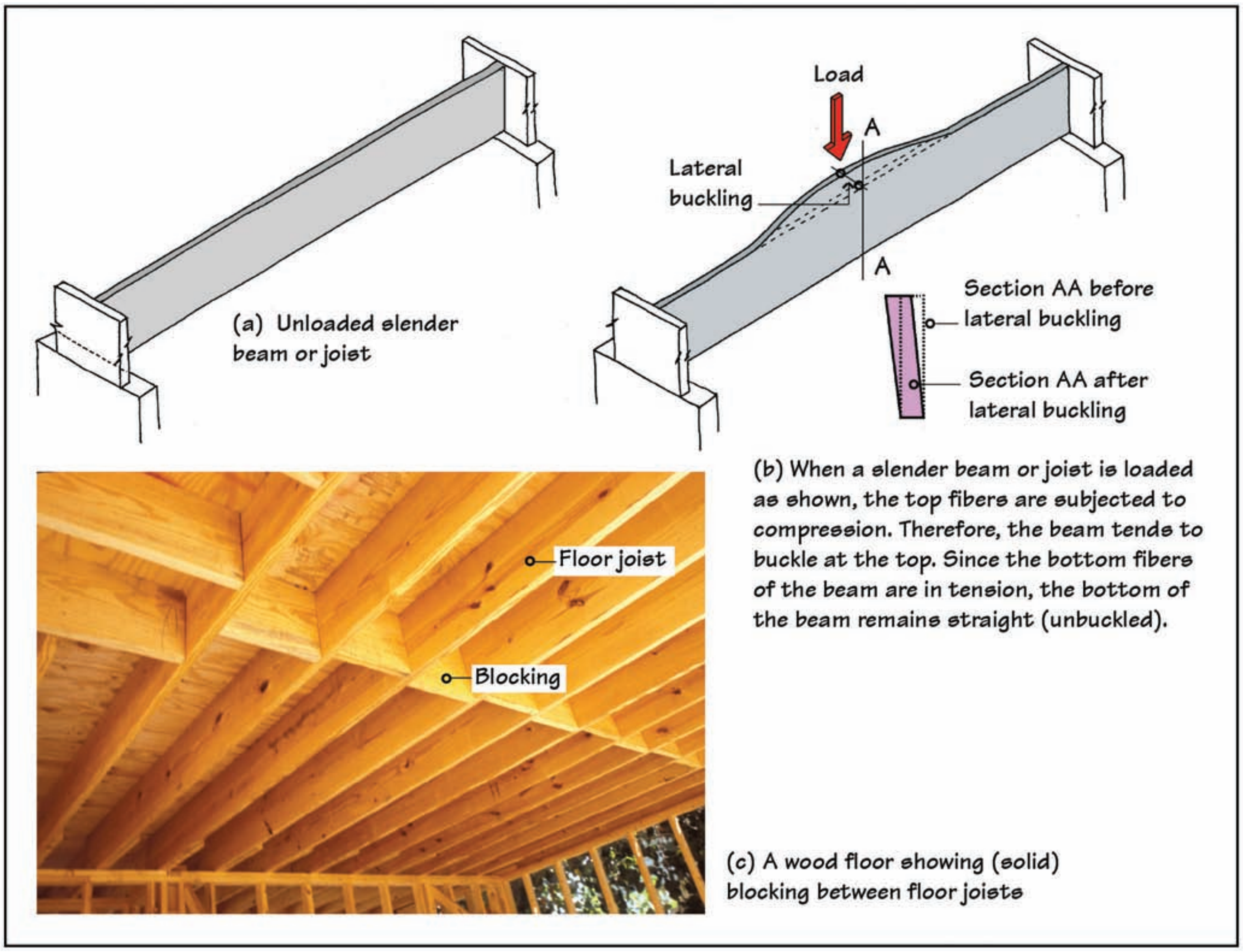

Load
A
Lateral buckling
A
Section AA before lateral buckling
Section AA after lateral buckling
(a) Unloaded slender beam or joist
(b) When a slender beam or joist is loaded as shown, the top fibers are subjected to compression. Therefore, the beam tends to buckle at the top. Since the bottom fibers of the beam are in tension, the bottom of the beam remains straight (unbuckled).
Floor joist
Blocking
(c) A wood floor showing (solid) blocking between floor joists

FIGURE 4.34 Lateral buckling of slender beams or joists. In wood floor joists (which are quite slender), lateral buckling is prevented by using solid blocking between joists (see also Section 15.6).

Lateral buckling can be verified by taking a 12-in.-long plastic ruler, using it as a horizontal beam, and subjecting it to a vertical load, as shown in Figure 4.34(b). We will see that the ruler will not bend downward but horizontally at the top. (Two persons, one to hold the ruler and the other to press it down, will facilitate the experiment.)

Buckling failure is not just a consideration for the entire structural member but also for its parts. Because of their slenderness, the vertical reinforcing bars in a concrete column have a tendency to buckle and break through the concrete cover under an axial load on the column. Horizontal ties are, therefore, provided along the height of the column to prevent this failure mode, Figure 4.35.

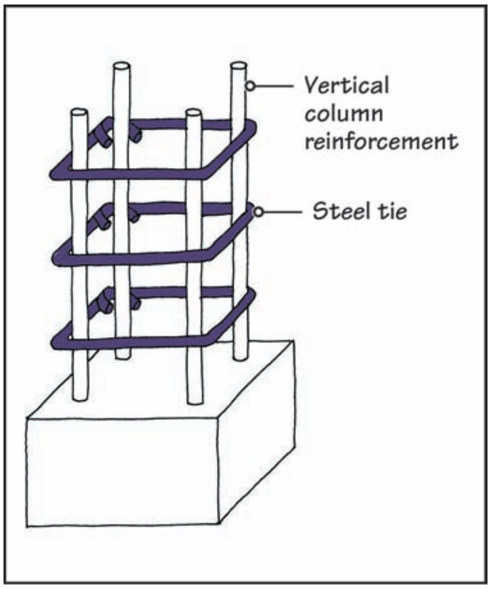

Vertical column reinforcement
Steel tie

FIGURE 4.35 Horizontal ties in a reinforced concrete column prevent the buckling of vertical reinforcement due to the compressive load on the column.

4.10 STRUCTURAL SAFETY

The most fundamental requirement of a structure is that it should be safe. A structure is safe if its strength is greater than the strength required to carry the loads imposed on it. The excess of the actual strength of the structure over that required to carry the loads is a measure of safety provided in the structure. Thus, the safety margin may be expressed as a ratio of actual strength to required strength—strength required to carry the loads:

$$\boxed{\text{Safety margin} = \frac{\text{actual strength}}{\text{required strength}}} \qquad \textbf{Eq. (4.4)}$$

With this definition, the safety margin must be greater than 1.0. If we could ascertain the loads that a structure is required to support with perfect certainty, if we were absolutely certain of the strength of the material, if all materials gave sufficient warning before failure, if the strength of materials did not deteriorate with time, and if the structural design procedures used had no ambiguity, then a safety margin slightly greater than 1.0 is all that would be needed.

The fact is, however, that none of these "ifs" can be ignored in practice. There are always uncertainties in the values of design loads used, and there is usually a great deal of variation in the strength of materials. For example, if several concrete cylinders were prepared from the same mix of concrete under identical conditions and were tested to failure using the same procedures and testing equipment, the results could vary by as much as 20%.

Additionally, materials deteriorate with time, and their deterioration is not the same under all conditions. Our design procedures are not exact and involve considerable approximation and generalization. Considering these uncertainties, it is necessary that the safety margin be much greater than 1.0.

The greater the uncertainty, the greater the safety margin needed. In a material such as steel, which is manufactured under controlled conditions, the safety margin used is relatively low. Concrete, on the other hand, is virtually always a site-manufactured material. Its strength is dependent on placing, compacting, and curing, all of which occur on site. Therefore, the safety margin used for concrete is higher.

Similarly, because wood is a naturally grown material, there is considerable variation (uncertainty) in its strength for the same specie and grade. The safety margin required in designing with wood is even higher than that required for concrete.

The safety margin is also dependent on the type of stress present. Usually, the margin is lower for bending stress or axial tension than for axial compression, shear, bearing, or buckling. The reason is that failure of a member in axial compression, shearing, bearing, and buckling is relatively more abrupt than in bending or axial tension, requiring a higher safety margin.

A large safety margin leads to uneconomical design. A judicious compromise is, therefore, needed between adequate safety and economic considerations.

STRUCTURAL SAFETY—ALLOWABLE STRESS

There are two ways in which safety is incorporated in a structure. One way is to limit the stress in members caused by loads to a value that is less than its failure stress. This limiting stress is called the *allowable stress.* The stress in the material caused by loads must be less than or equal to the allowable stress. The ratio of the failure stress to the allowable stress is the safety margin, which is commonly called the *factor of safety:*

$$\boxed{\text{Factor of safety} = \frac{\text{failure stress}}{\text{allowable stress}}} \qquad \textbf{Eq. (4.5)}$$

For example, if the failure stress of a material is 2,000 psi and if a factor of safety of 2.0 is used, the allowable stress of that material is 2,000/2.0 = 1,000 psi.

STRUCTURAL SAFETY—LOAD FACTOR AND RESISTANCE FACTOR

An alternative method of incorporating safety in structures is to inflate the value of loads on the structure, that is, to design the structure for loads that are greater than those that will actually be present on the structure. This method is more sophisticated because the loads can be inflated based on the degree of uncertainty present in their determination. Load inflation is achieved by multiplying the loads by suitable multiplication factors, called the *load factors.* Because a load factor represents inflation in the value of a load, a load factor is greater than 1.0.

The load factor is relatively small for dead loads, because the uncertainty in their determination is small. The load factor is larger for live loads because of greater uncertainty in their determination.

Because there is some uncertainty in the determination of the strength of materials, the strength of the material is reduced by a factor called the *resistance factor.* The resistance factor is less than 1.0. This method of structural design is, therefore, referred to as the *load resistance factor method,* as opposed to the *allowable stress method* described previously.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

21. The primary purpose of longitudinal steel bars in a reinforced concrete beam is to overcome the weakness of concrete in tension.
- **a.** True
- **b.** False

22. A material that is weak in tension is
- **a.** strong in shear.
- **b.** weak in shear.
- **c.** no relationship between the shear and tensile strengths of a material.

23. A material that is weak in tension is
- **a.** strong in bending.
- **b.** weak in bending.
- **c.** no relationship between the tensile and bending strengths of a material.

24. The stirrups in a reinforced concrete beam are used to
- **a.** increase the strength of the beam in bending.
- **b.** reduce the deflection of the beam.
- **c.** increase the durability of the beam.
- **d.** increase the strength of the beam in shear.
- **e.** none of the above.

25. The bearing strength of a material is closely related to its
- **a.** bending strength.
- **b.** tensile strength.
- **c.** compressive strength.
- **d.** modulus of elasticity.
- **e.** none of the above.

26. In a steel column that rests on a concrete footing, the area of the bearing plate used is generally
- **a.** greater than the cross-sectional area of the column.
- **b.** equal to the cross-sectional area of the column.
- **c.** smaller than the cross-sectional area of the column.

27. The primary purpose of ties in a reinforced concrete column is to
- **a.** prevent the buckling of vertical reinforcement in the column.
- **b.** prevent the crushing of concrete.
- **c.** increase the shear resistance of the column.
- **d.** none of the above.

28. The horizontal blocking in wood studs helps prevent
- **a.** compressive failure of studs.
- **b.** shear failure of studs.
- **c.** tensile failure of studs.
- **d.** buckling of studs.

29. The allowable stress in a material is generally
- **a.** equal to its ultimate stress.
- **b.** less than its ultimate stress.
- **c.** greater than its ultimate stress.
- **d.** none of the above.

30. In most materials, the safety margin for compressive stress and bending stress is the same.
- **a.** True
- **b.** False

REVIEW QUESTIONS

1. What are the units of stress in the U.S. system of units and the SI system of units?
2. A l-in.-diameter steel bar is subjected to a tensile force of 30 kips. Determine the stress in the bar.
3. If the bar in Problem 2 is 10 ft long, determine the elongation in the bar. The modulus of elasticity of steel is 29×10^6 psi.
4. Sketch the stress-strain diagram of low-carbon (mild) steel, showing all of its important parts, and explain why steel should not be stressed beyond its yield stress.
5. Explain the modulus of elasticity. Which property of the material does it represent? Give the approximate values of the modulus of elasticity of steel, concrete, and wood.
6. Explain the difference between:
   (a) elasticity and modulus of elasticity of a material
   (b) brittleness and ductility of materials
7. Explain with the help of a three-dimensional sketch the reason for bending inefficiency, that is, why the strength of a material in a component is not fully utilized when the component is subjected to bending.
8. Using sketches and notes, explain how we increase the bending efficiency of building components.
9. Explain with the help of a sketch why a brittle material is weak in shear.
10. Explain what is bearing strength of a material and how it differs from the material's compressive strength.
11. Explain the concept of buckling. Explain whether buckling would occur if a member is subjected to bending. What measures do we adopt to prevent the buckling failure of building components?
12. If the ultimate strength of a material is 6,000 psi and the factor of safety is 2.5, determine the allowable stress of the material.

CHAPTER 5

Properties of the Envelope–I
(Thermal Properties)

CHAPTER OUTLINE

5.1 ENERGY USE IN BUILDINGS AND THERMAL COMFORT

5.2 THE UNITS OF MEASUREMENT FOR ENERGY

5.3 THREE MODES OF HEAT FLOW THROUGH MATERIALS AND ASSEMBLIES

5.4 R-VALUE OF A BUILDING COMPONENT

5.5 USE OF GASES OTHER THAN AIR IN BUILDING ASSEMBLIES

5.6 R-VALUE OF A MULTILAYER ASSEMBLY IN SERIES COMBINATION

5.7 SURFACE RESISTANCES

5.8 SURFACE EMISSIVITY AND R-VALUES OF AIR SPACES

5.9 SURFACE COLOR OF ENVELOPE ASSEMBLIES

5.10 MULTILAYER ASSEMBLY IN PARALLEL COMBINATION—THE U-FACTOR

5.11 THERMAL BRIDGING

5.12 F-FACTOR AND C-FACTOR

5.13 U-FACTOR, F-FACTOR, AND C-FACTOR—A SUMMARY

5.14 WHERE AND HOW MUCH TO INSULATE—THE BUILDING THERMAL ENVELOPE

5.15 THE INTERNATIONAL ENERGY CONSERVATION CODE

5.16 CONTINUOUS ENVELOPE INSULATION REQUIRED

5.17 THERMAL MASS

PRINCIPLES IN PRACTICE: COMMONLY USED INSULATING MATERIALS

PRINCIPLES IN PRACTICE: ADVANCED INSULATING MATERIALS

In Chapters 3 and 4, we discussed loads on buildings and the structural properties of materials. The focus was on the structural system—the components that work together to support and give form to a building. This chapter and the following chapter focus on the performance properties of the building's enclosure. (In practice, several different names are used for the building's enclosure, including envelope and skin. In this text, we generally use the term *building envelope*.)

The building envelope is one of the most important parts of a building, from both the aesthetic as well as the performance perspective. Aesthetically, it is where the design team invests a great deal of effort. From the performance perspective, the role of the envelope is to separate the interior of the building from the exterior environment: heat and cold (i.e., thermal), air, water vapor, (liquid) water, noise, dust, insects, and so on. Therefore, in addition to being structurally adequate, the envelope must mediate between the exterior and the interior of the building so that required interior environmental conditions are achieved.

Of the environmental parameters mentioned, four of them—thermal, air, vapor, and water—impact the design of the envelope most significantly. They are also interrelated because the flow of air and vapor through the envelope impact the building thermally, and vapor and water are essentially the same material but in different states (gas and liquid, respectively). The next chapter (Chapter 6) deals with properties related to air and water vapor flow through the envelope, and Chapter 27 deals with rainwater infiltration through the envelope.

In this chapter, properties related to heat flow through the envelope are discussed, an understanding of which is essential to comprehending the envelope-related provisions of the International Energy Conservation Code (IECC). The IECC, which has been adopted throughout the United States, has become increasingly more stringent with each revision cycle. For example, its recent requirement for continuous envelope insulation is forcing changes in construction detailing of several facade assemblies.

5.1 ENERGY USE IN BUILDINGS AND THERMAL COMFORT

Providing thermal comfort in buildings has been an important design objective from the earliest times. The considerations of climate and manipulation of building form and materials to produce a comfortable building have always had a profound influence on building design. The provision of fireplaces in homes in cold climates, the use of thick adobe walls in hot-dry regions of Northern India, and wind scoops on roofs in coastal areas of the Middle East, are examples of climate-sensitive design before the discovery of electro-mechanical means of heating and cooling buildings.

Advances in heating, ventilating, and air-conditioning (HVAC) equipment in the early twentieth century made it possible to achieve interior comfort independent of the considerations of site, building form, or climate. The simultaneous discovery of structural materials that permitted long-span and high-rise buildings, followed by the extensive use of glass on building facades, resulted in a massive surge in the use of energy in buildings.

During the 1970s, two facts became abundantly clear: (a) the world's energy resources are finite and (b) the excessive use of energy is damaging the earth's environment. Consequently, energy conservation became an important design objective, which led to a substantial reorientation in architectural thinking. Consideration of thermal properties and thermal behavior of buildings assumed greater importance. The building industry reacted by producing materials and equipment that are thermally more efficient, and the design community responded by insulating the building envelope against heat gain and heat loss. In fact, today's building envelope is a multilayered, often complex assembly of materials and components.

As shown in Figure 5.1, an energy-conserving building design is a function of several variables. It includes the consideration of the outside climate, site conditions, building orientation and shape, building services (HVAC, lighting, water supply including hot water, horizontal and vertical transportation, waste management, and so on), and thermal properties of the building envelope.

Although all factors shown in Figure 5.1 are important, the envelope is the single most important factor because the envelope components are permanent and are not subjected to the recurring costs of maintenance, failure, or replacement, unlike the equipment associated with building services. In this chapter, only the thermal properties of the envelope are discussed.

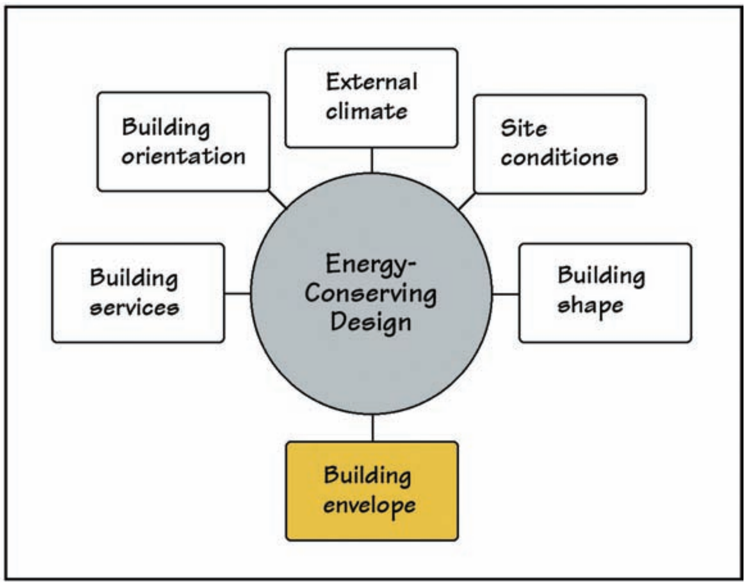


FIGURE 5.1 Factors that affect energy-conserving building design. The focus of this chapter is on the elements of energy-conserving building envelope design.

5.2 THE UNITS OF MEASUREMENT FOR ENERGY

Because thermal properties of materials and assemblies are related to energy flow through them, an understanding of the units of measurement of energy is necessary. In the SI system of units, energy is measured in Joules (J), and the rate of energy flow through a material is measured in Joules per second (J/s), which is called Watts (W). Both Joule and Watt are small units. Therefore, kilojoule (kJ) and kilowatt (kW) are commonly used.

In the U.S. system of units, the unit for energy is the British thermal unit (Btu), and the corresponding unit for rate of energy flow is Btu per hour (Btu/h). Btu is a much larger unit than Joule. 1 Btu = 1,055 J, and 1 Btu/h = 0.293 J/s = 0.293 W.

5.3 THREE MODES OF HEAT FLOW THROUGH MATERIALS AND ASSEMBLIES

From our daily experience, we know that if two objects, which are at different temperatures, are placed in contact with (or close to) each other, the temperature of the warmer object decreases and that of the cooler object increases. This phenomenon occurs because heat flows from an object at a higher temperature to that at a lower temperature, Figure 5.2. Heat transfer will continue until the temperature of the two objects becomes equal. There are three modes by which heat transfer can take place: conduction, convection, and radiation.

CONDUCTION—THE MODE OF HEAT FLOW THROUGH SOLIDS

Conduction is the phenomenon of heat transfer between the molecules of a substance that are in contact with each other. It is the only mode of heat transfer within solids and is characterized by physical contact between the molecules in the substance. When one end of a solid substance is heated, the molecules in the neighborhood of the heated end begin to vibrate about their mean positions with a higher average velocity. Because of the physical contact between the molecules of the substance, the increased vibrational energy in the heated molecules is transferred to adjacent cooler molecules, which in turn transfer their increased energy to still cooler molecules in their neighborhood, and so on.

CONVECTION—THE MODE OF HEAT FLOW IN FLUIDS (GASES AND LIQUIDS)

Convection occurs only in fluids (gases and liquids) and may be described as energy transfer by actual bulk motion of a gas (such as air) or liquid (such as water). A familiar example of convection is the heating of water on a stove. When water in a container is placed on a stove, the water particles nearest the burner become lighter in density as they are heated. Being lighter, these particles rise to the top and are replaced by colder (and hence heavier) particles of water from above. The colder particles are heated again and rise to the top, and the cycle continues as long as the water is being heated. This process creates motion within the fluid.

In addition to the transfer of energy by bulk motion, which creates fluid flow, a small amount of energy is also transferred by conduction in fluids because of the physical contact between the fluid particles. However, the dominant mode of heat transfer in fluids is by convection, that is, the movement of fluid particles.

The process of heat transfer described by the heating of water on a stove is called *natural convection*. Natural convection results from density changes in the fluid. Convection may also occur without changes in the density of fluid, in which case it is called *forced convection*. Forced convection is produced by fans, pumps, and wind motion.

RADIATION—THE MODE OF HEAT FLOW IN GASES AND VACUUM

Radiation is the transfer of energy between two objects in the form of electromagnetic waves. Thus, the heat and light received from the sun, from a burning candle, or from an electric lamp reach us by electromagnetic radiation. Unlike conduction and convection, radiation does not require a medium to travel, that is, it can travel in vacuum. This property allows radiation from the sun to reach the earth through the vast realm of space.

It is important to appreciate that heat radiation is a form of electromagnetic radiation, and all electromagnetic radiation is transformed into heat when absorbed by an object. Electromagnetic radiation can exist in a variety of wavelengths, each with different characteristics. Some of the segments of electromagnetic radiation are infrared, visible (light), ultraviolet, X-rays, and gamma rays.

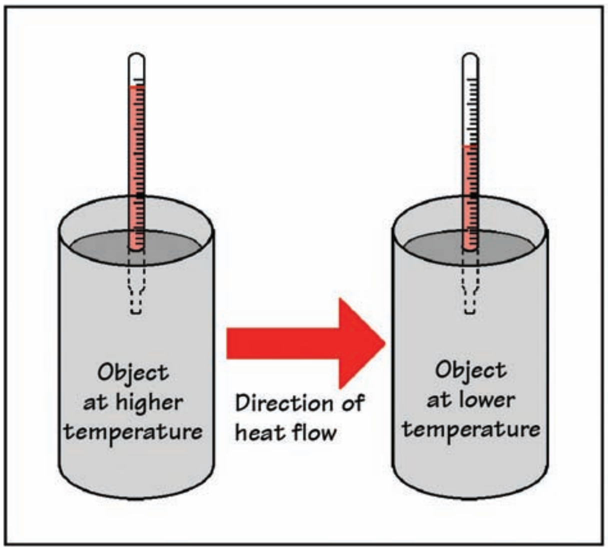


FIGURE 5.2 Heat flows from an object at a higher temperature to an object at a lower temperature.

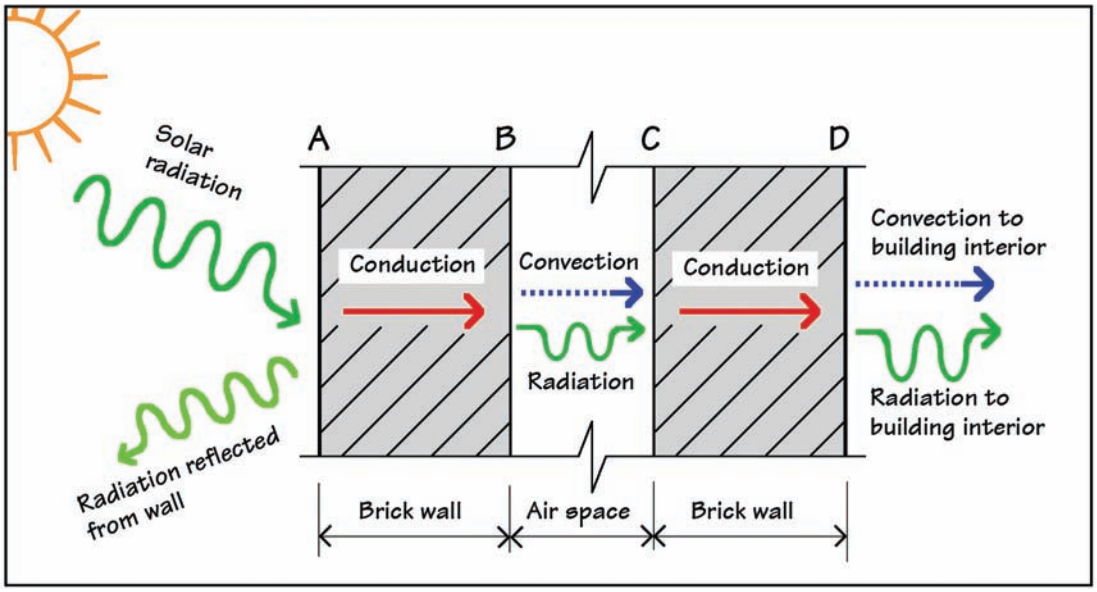

Solar radiation
Radiation reflected from wall
A
B
C
D
Conduction
Convection
Radiation
Conduction
Convection to building interior
Radiation to building interior
Brick wall
Air space
Brick wall

FIGURE 5.3 Modes of heat transfer from solar radiation through a brick cavity wall.

Thus, although the radiation from the sun consists of ultraviolet, visible, and infrared radiations, all three components of solar radiation are converted to heat when they are absorbed by a building surface. Similarly, all radiation from an electric lamp in a room is converted to heat as it gets absorbed by the occupants, furniture, room surfaces, and the room air.

SIMULTANEITY OF CONDUCTION, CONVECTION, AND RADIATION

During the process of heat transfer through a building envelope, all three modes usually come into play simultaneously. Thus, to reduce heat transfer through the envelope, all three modes must be considered, and the heat-transfer potential of each mode must be reduced.

Consider the section through the brick cavity wall shown in Figure 5.3. Energy from the sun reaches the wall by radiation and is partly absorbed and partly reflected by the wall's exterior surface. The absorbed energy then travels by conduction through the wall (from surface A to surface B) until it reaches the air space.

Inside the air space (from surface B to surface C), the heat-transfer mode changes to radiation and convection. The subsequent mode is conduction through the inner layer of the wall (from surface C to surface D). Finally, the energy is transferred from the inner surface of the wall (surface D) to indoor air, room surfaces, furniture, and occupants by convection and radiation.

5.4 R-VALUE OF A BUILDING COMPONENT

The term R is called *thermal resistance*, or simply the *R-value*. It is the measure of the ability of a component to resist the flow of heat through it. The R-value is related to heat flow primarily by conduction. To understand the concept, consider a rectangular plate (such as a wall or roof) of thickness L, as shown in Figure 5.4. Let the surface temperatures of the two faces of the plate be t_1 and t_2. If t_2 is greater than t_1, heat will travel from face 2 to face 1. Experiments have shown that the rate of heat transfer by conduction from face 2 to face 1 is given by

$$\boxed{Q_c = \frac{(t_2 - t_1)}{\rho L}} \qquad \textbf{Eq. (5.1)}$$

Where, Q_c is the rate of heat conduction in Btu/h through 1 ft^2 of the plate (Btu/h-ft^2).

Equation (5.1) shows that the rate of heat conduction, Q_c, through the plate is directly proportional to the difference between the surface temperatures of the two faces of the plate. If there is no difference between the surface temperatures—that

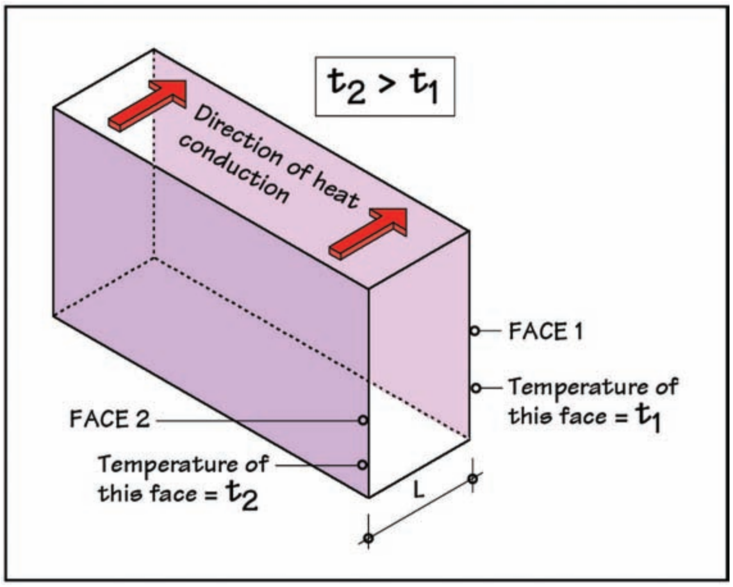

t2 > t1
Direction of heat conduction
FACE 1
Temperature of this face = t1
FACE 2
Temperature of this face = t2
L

FIGURE 5.4 Heat transfer by conduction through a plate of thickness L.

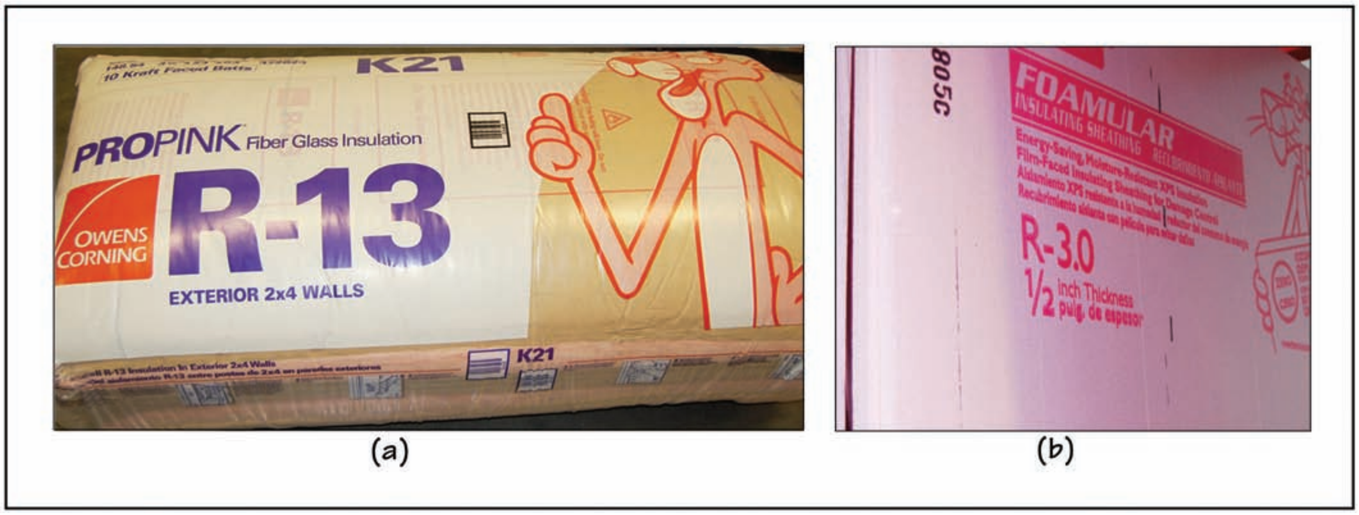


FIGURE 5.5 **(a)** A bag containing batts of $3\frac{1}{2}$-in.-thick, R-13 fiberglass insulation. **(b)** R-3.0 extruded polystyrene (XPS) board insulation.

is, if $(t_2 - t_1)$ is zero—no heat conduction will occur. Additionally, the rate of heat conduction is inversely proportional to the thickness, L, of the plate. This means that the greater the thickness of the plate, the smaller the amount of heat conducted through it.

The term ρ in Equation (5.1) is called *thermal resistivity*. Thermal resistivity is a property of the material and is, therefore, constant for the material. If the value of ρ is large, the rate of heat conduction through the plate is small. Such a material is called a *thermal insulator* or an *insulating material*. Conversely, if the value of ρ is small, the rate of heat conduction through the plate is large. Such a material is called a *thermal conductor*.

If we now replace ρL in Equation (5.1) by R, it becomes:

$$\boxed{Q_c = \frac{(t_2 - t_1)}{R}} \qquad \textbf{Eq. (5.2)}$$

The term R refers to *thermal resistance*, and a component with a high R-value is more insulating (resistant to the flow of heat) than a component with a low R-value. It is the R-value that is generally quoted in referring to the insulating value of a building component. Thus, we speak of the R-value of a component, such as R-10 or R-11. Most insulating products are labeled with their R-values, Figure 5.5.

From Equation (5.2), the units of R-value are (ft^2-°F-h)/Btu. The units of ρ are [(ft^2-°F-h)/(Btu-in.)], Table 5.1. Because both of these units are rather long and complex, we usually omit the units in practice—a practice that we will follow in this text.

When the R-value of a component is given in the SI system of units, it is usually referred to as the *RSI-value*. Thus, if the R-value of a component is R-10, its RSI-value is 1.76, which is referred to as RSI-1.76. Table 5.1 also gives the conversion factors for R-values and ρ-values.

DIFFERENCE BETWEEN R-VALUES AND ρ-VALUES

It is important to note again that the ρ-value is a property of the material, whereas the R-value is a property of the component of a certain thickness. Because they are related to each other by the relationship $R = \rho L$, where L is the thickness of the component, the ρ-value is, in fact, the R-value of a component whose thickness is 1 in. Thus, if we know the ρ-value of a material, we can determine the R-value of a component of any thickness. For example, if the ρ-value of a material is 2.5, then the R-value of a 6-in.-thick component made of that material is $2.5(6) = 15.0$; that is, the R-value of this component is 15.

Because the ρ-value is a material property, it is the ρ-value that is used for comparing the insulating effectiveness of materials. Again, a material with a higher ρ-value is a better thermal insulator. The ρ-values of some commonly used materials are given in Table 5.2.

TABLE 5.1 UNITS OF MEASUREMENT OF R-VALUE AND ρ-VALUE

	Unit	
Quantity	U.S. System of Units	S.I. System of Units
R-value	$\frac{ft^2 \cdot h \cdot {}^\circ F}{Btu}$	$\frac{m^2 \cdot K}{W}$
ρ-value	$\frac{ft^2 \cdot h \cdot {}^\circ F}{Btu \cdot in.}$	$\frac{m \cdot K}{W}$

To convert an R-value to RSI-value, multiply R-value by 0.176. To convert an RSI-value to R-value, multiply RSI-value by 5.68.

EFFECT OF DENSITY AND MOISTURE CONTENT ON THE ρ-VALUE

As a general rule, a low-density material has a high ρ-value. Being fibrous, granular, or cellular in structure, a low-density material has air trapped within its voids. Because air has a high ρ-value, a low-density material is a better insulator than a

TABLE 5.2 APPROXIMATE ρ-VALUES OF SELECTED BUILDING MATERIALS

Material	ρ-value (R-value of 1 in. thick material) $\frac{ft^2 \cdot h \cdot °F}{Btu \cdot in.}$
Metals	
Steel	0.0032
Copper	0.00032
Aluminum	0.0032
Ceramic Materials	
Clay brick	0.20
Concrete (normal weight)	0.15
Concrete (structural lightweight)	0.25–0.35 (depends on density)
Concrete masonry	Depends on type of concrete
Limestone	0.15
Sandstone	0.18
Glass sheet	0.14
Gypsum wallboard, gypsum sheathing	0.60
Portland cement plaster (stucco)	0.30
Wood-Based Materials	
Solid lumber (12% moisture content)	1.2
Plywood; OSB	0.14
Fiberboard	2.4
Wood charcoal	2.2
Insulating Materials	
Silica aerogel blanket	10.0
Polyisocyanurate (ISO) board—aged value	6.0
Polyurethane foam (PUR)—aged value	5.5
Extruded polystyrene (XPS) board—aged value	5.0
Expanded polystyrene (EPS) board	4.0
Perlite board (low-slope roof insulation)	2.8
Insulating concrete (low-slope roof insulation)	1.2–1.7
Fiberglass (batt; blanket; loose-fill)	3.5
Gases, Vacuum, and Water	
Air*	5.6
Air (air spaces in building assemblies)	(See Table 5.3)
Argon*	8.9
Krypton*	15.0
Hydro-chloro-fluoro-carbon (HCFC) gas	15.0
Vacuum**	40.0–50.0
Vacuum insulated panel	30.0–35.0
Water	0.24

Multiply the values given here by 0.176 to obtain corresponding value in SI system of units for 1-in.-thick material. The unit for that value is:

$$\frac{m^2 \cdot K}{W \cdot in.}$$

In plastic foam insulations (ISO, PUR, and XPS), hydro-chloro-fluoro-carbon (HCFC) gas is currently used as blowing agent, which has an adverse effect on the environment. Hydro-fluoro-olefin (HFO) gas is gradually replacing HCFC.

* The ρ-values for gases represent heat conduction by molecular collisions and vary considerably depending on the physical dimension of spaces within which they are held.

** Represents value at the center of panel or space.

Reference: The values given here have been obtained from several sources, and are approximate. Refer to manufacturer's literature for precise values.

high-density material. In fact, still air is one of the best thermal insulators available. Circulating air cannot be a good insulator because the circulation of air increases convective heat flow, thereby reducing the ρ-value.

In other words, the basic requirement of an insulating material is that the solid constituents of the material must divide its volume into such tiny air spaces that air cannot circulate within them. This characteristic ensures that convective heat transfer is negligible. It also implies that all insulating materials are low-density materials.

Another important parameter that affects the ρ-value is the moisture content of the material. Water has a much lower ρ-value than air (ρ-value of air = 5.6 and ρ-value of

Example 5.1
(R-Value from ρ- Value)

Determine the R-value of (a) a 6-in.-thick concrete wall, (b) a 6-in.-thick fiberglass blanket, and (c) a $\frac{1}{4}$-in.-thick glass sheet.

Solution

From Table 5.2, the ρ-value of concrete, fiberglass, and glass sheet are 0.15, 3.5, and 0.14, respectively.

a. For a 6-in.-thick (normal-weight) concrete wall, $R = \rho L = (0.15)(6) = 0.9$.
b. For a 6-in.-thick fiberglass blanket, $R = \rho L = (3.5)(6) = 21.0$.
c. For a $\frac{1}{4}$-in.-thick glass sheet, $R = \rho L = (0.14)(0.25) = 0.035$.

Note that although the concrete wall and the fiberglass blanket are both of the same thickness, the fiberglass blanket is nearly 21.0/0.9 = 23 times more effective as a thermal insulator than the concrete wall. In other words, it will take a nearly 23(6) = 138-in.-thick concrete wall to provide the same thermal insulation as a 6-in.-thick fiberglass blanket. Also note that the R-value of a sheet of glass is virtually zero.

water = 0.24, Table 5.2). Because a moist material has water trapped inside its pores in place of the air, its ρ-value is lower than if it is dry. It is, therefore, important to ensure, in the detailing of buildings, that insulating materials remain dry throughout their useful life spans. This fact is important because most insulating materials due to their location are particularly vulnerable to water absorption from rain. In cold climates where condensation of water vapor within insulating materials is an additional hazard, vapor retarders are installed in roof and exterior wall assemblies (see Sections 6.5 to 6.7).

5.5 USE OF GASES OTHER THAN AIR IN BUILDING ASSEMBLIES

Although most insulating materials derive their insulating property from the entrapment of tiny volumes of air, a few other gases are also used for the same purpose because they are better insulators than air. A commonly used group of insulating materials, referred to as *plastic foams* (or *foamed plastics*, discussed at the end of this chapter) contain hydro-chloro-fluoro-carbon (HCFC) gas, which is approximately 2.5 times more insulating than air (see Table 5.2).

Foamed plastics that trap HCFC gas are manufactured using HCFC as a foaming agent in a liquid polymer that solidifies as it foams. To ensure that HCFC gas does not leak out, foamed plastics have a closed-cell structure, Figure 5.6(a). A type of foamed plastic that

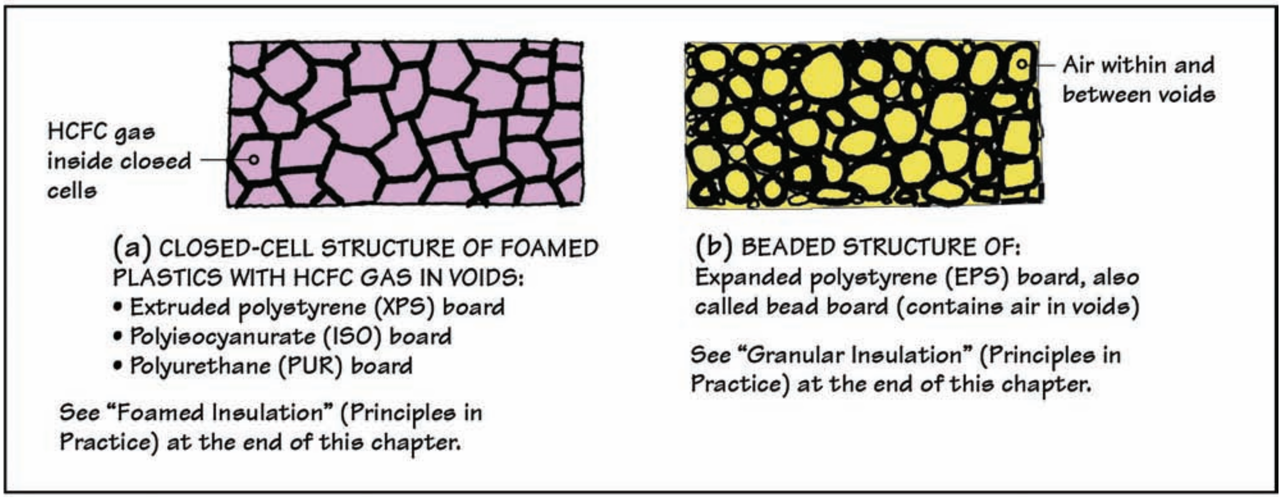

HCFC gas inside closed cells
(a) CLOSED-CELL STRUCTURE OF FOAMED PLASTICS WITH HCFC GAS IN VOIDS:
• Extruded polystyrene (XPS) board
• Polyisocyanurate (ISO) board
• Polyurethane (PUR) board
See "Foamed Insulation" (Principles in Practice) at the end of this chapter.
Air within and between voids
(b) BEADED STRUCTURE OF: Expanded polystyrene (EPS) board, also called bead board (contains air in voids)
See "Granular Insulation" (Principles in Practice) at the end of this chapter.

FIGURE 5.6 Cellular structures of various plastic foam insulations.

contains air in the voids does not have a closed-cell structure, and is made from foamed beads, Figure 5.6(b). A board made from beads is called an *expanded polystyrene* (*EPS*) board, whose **ρ**-value is lower than foams containing HCFC gas—extruded polystyrene (XPS), polyisocyanurate (ISO), and polyurethane (PUR).

Despite the closed-cell structure of plastic foams containing HCFC gas, some gas finds its way into the atmosphere. Therefore, air is able to permeate into the cell cavities of these foams, driving HCFC gas out from the edges and ends of a board. The steady outward migration of HCFC gas means that the R-value of such plastic foams decreases with time. Therefore, in referring to the R-value of a plastic foam with HCFC gas, we generally quote its *stabilized* or *aged* R-value. Long-term thermal resistance (LTTR) is another term used for the stabilized R-value, and manufacturers label their products, containing HCFC gas, with the LTTR value, Figure 5.7. LTTR-value is lower than the R-value immediately after the plastic foam's manufacture. In most cases, the R-value of such a material stabilizes after six months, after which the decrease in R-value is negligible.

Two other gases that are commonly used in building assemblies are argon and krypton. The insulating property of argon is higher than air, and that of krypton is even higher than argon, Table 5.2. They both are used in the space between two glass sheets in an insulating glass unit (see Chapter 30).

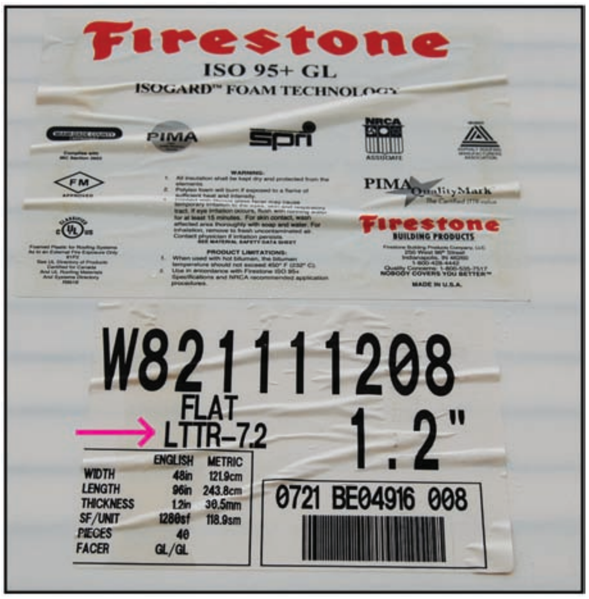


FIGURE 5.7 R-value label on a bundle of polyisocyanurate (ISO) boards showing the LTTR value of 7.2 for board thickness of 1.2 in.

PRACTICE **QUIZ**

Each question has only one correct answer. Select the choice that best answers the question.

1. Apart from the climate of the location, the other factors that affect energy-conscious building design are
a. building orientation and building shape.
b. building envelope.
c. site conditions.
d. all of the above.
e. (a) and (b).

2. IECC is an acronym for
a. Institute for Energy Conversion and Conservation.
b. Institute for Energy Conservation and Codification.
c. International Energy Conservation Code.
d. International Energy Cooperation Council.
e. none of the above.

3. The unit for the measure of energy in the U.S. system of units is
a. calorie.
b. Joule.
c. Btu.
d. Watt-hour.
e. all of the above.

4. The unit for the measure of energy in the SI system of units is
a. calorie.
b. Joule.
c. Btu.
d. Watt.

5. Within a solid, the mode of heat transfer is by
a. conduction.
b. convection.
c. radiation.
d. both (a) and (b).
e. both (b) and (c).

6. Within an air space (cavity), the mode of heat transfer is primarily by
a. conduction.
b. convection.
c. radiation.
d. both (a) and (b).
e. both (b) and (c).

7. Air is a good thermal insulator, provided that it exists in large volumes.
a. True
False

8. The R-value of a 2-in.-thick material is 4.0. What is the R-value of the same material if its thickness is 1 in.?
a. 1.0
b. 0.5
c. 6.0
d. 8.0
e. None of the above

9. The R-value of a building assembly in the SI system is referred to as the
a. R-value (SI).
b. SI-value.
c. RS-value.
d. RSI-value.
e. none of the above.

10. A wet or moist material provides a higher R-value than if the same material is dry.
a. True
b. False

11. One of the main reasons for using HCFC gas in some insulating materials is that it
a. makes the material noncombustible.
b. makes the material more economical.
c. makes the material more resistant to decay.
d. increases the strength of the material.
e. none of the above.

12. Insulating materials that contain HCFC gas within their cells have a higher R-value than those that contain air within their cells.
a. True
b. False

13. Which of the following insulating materials contain HCFC gas within their voids?
a. Extruded polystyrene
b. Polyisocyanurate
c. Polyurethane
d. All of the above
e. Only (b) and (c)

14. For the same thickness, which of the following materials has the highest R-value?
a. Extruded polystyrene
b. Expanded polystyrene
c. Polyisocyanurate
d. Fiberglass
e. Gypsum

15. For the same thickness, which of the following materials has the smallest R-value?
a. Extruded polystyrene
b. Expanded polystyrene
c. Polyisocyanurate
d. Fiberglass
e. Gypsum

16. The R-value of a 1-in.-thick extruded polystyrene board is 5.0. If the R-value of a 1-in.-thick brick wall is 0.2, how thick should the brick wall be to equal the R-value of 1-in.-thick extruded polystyrene?
a. 10 in.
b. 5 in.
c. 50 in.
d. 2.5 in.
e. None of the above

17. The concept of *aged R-value* is applicable to
a. all insulating materials.
b. insulating materials that contain HCFC gas.
c. fiberglass insulation.
d. perlite board insulation.
e. all building materials.

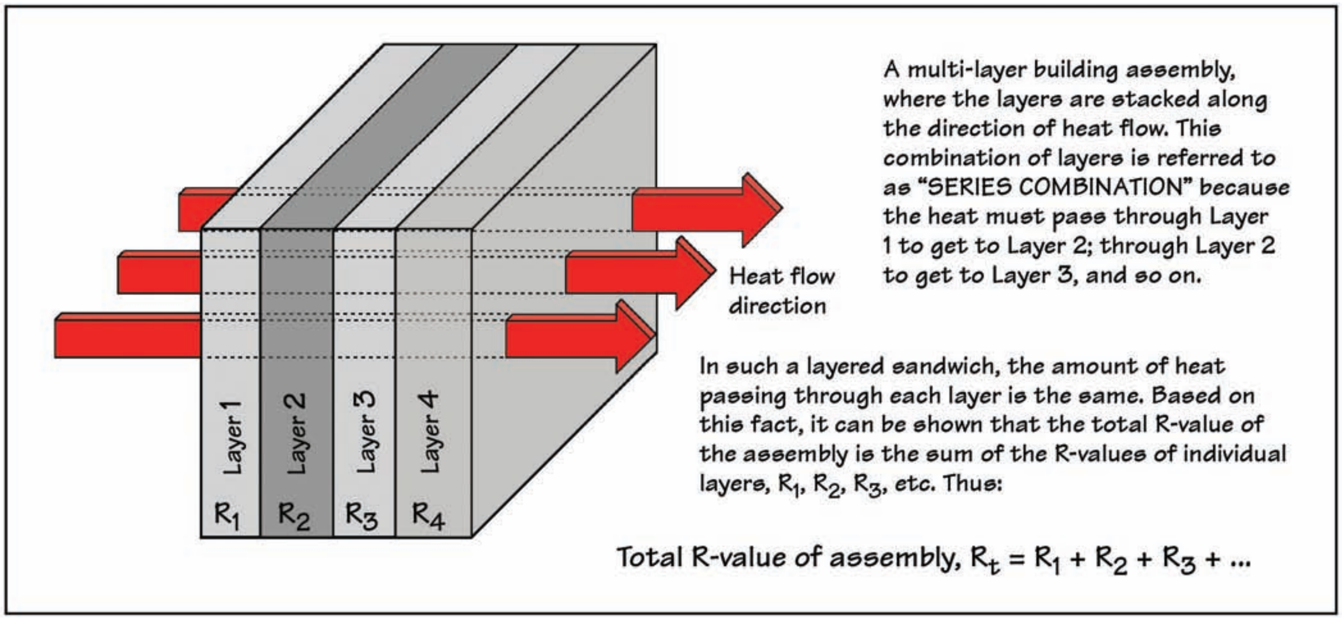
5.6 R-VALUE OF A MULTILAYER ASSEMBLY IN SERIES COMBINATION

Usually a wall or roof assembly consists of several layers of different materials, as shown in Figure 5.8. For example, the wall shown in Figure 5.3 consists of three layers of materials: a layer of brick, a layer of air space, and a second layer of brick. Using the laws of physics, it can be shown that the total resistance of a multilayer assembly, shown in Figure 5.8, is obtained by adding the R-values of the individual layers:

$$\boxed{R_t = R_1 + R_2 + R_3 + \cdots} \qquad \textbf{Eq. (5.3)}$$

Where, R_t is the total resistance of the multilayer assembly, and R_1, R_2, R_3, . . ., are the resistances of layer 1, layer 2, layer 3, and so on, respectively.

The combination of layers in Figure 5.8 is referred to as *series combination*, to be distinguished from the *parallel combination*, discussed in Section 5.10. In a series combination, the layers are stacked one behind the other, and the amoumt of heat passing through each layer is the same.



A multi-layer building assembly, where the layers are stacked along the direction of heat flow. This combination of layers is referred to as "SERIES COMBINATION" because the heat must pass through Layer 1 to get to Layer 2; through Layer 2 to get to Layer 3, and so on.

In such a layered sandwich, the amount of heat passing through each layer is the same. Based on this fact, it can be shown that the total R-value of the assembly is the sum of the R-values of individual layers, R_1, R_2, R_3, etc. Thus:

Total R-value of assembly, $R_t = R_1 + R_2 + R_3 + \ldots$

FIGURE 5.8 R-value of a multilayer assembly—layers in series combination. The heat flow through each layer is the same.

Example 5.2

(Estimating the Total R-Value of an Assembly)

Calculate the total R-value of a wall assembly that consists of 2-in.-thick extruded polystyrene (XPS) insulation sandwiched between an 8-in.-thick (nominal) brick wall and a 4-in.-thick (nominal) brick wall, as shown in Figure 5.9.

Note: The actual thickness of an 8-in.-thick (nominal) brick wall is $7\frac{5}{8}$ in., and that of a 4-in.-thick brick wall is $3\frac{5}{8}$ in. (see Section 24.5).

Solution

From Table 5.2, the ρ-values of brick wall and extruded polystyrene (XPS) insulations are 0.2 and 5.0, respectively. The total R-value of the assembly is determined as follows:

Element	R-value
4-in.-thick brick wall	3.625(0.2) = 0.725
2-in.-thick XPS board	2.0(5.0) = 10.0
8-in.-thick brick wall	7.625(0.2) = 1.525

$$R_t = 0.725 + 10.0 + 1.525 = 12.25$$

Because an R-value is given by the nearest whole number, the wall is an R-12 wall.

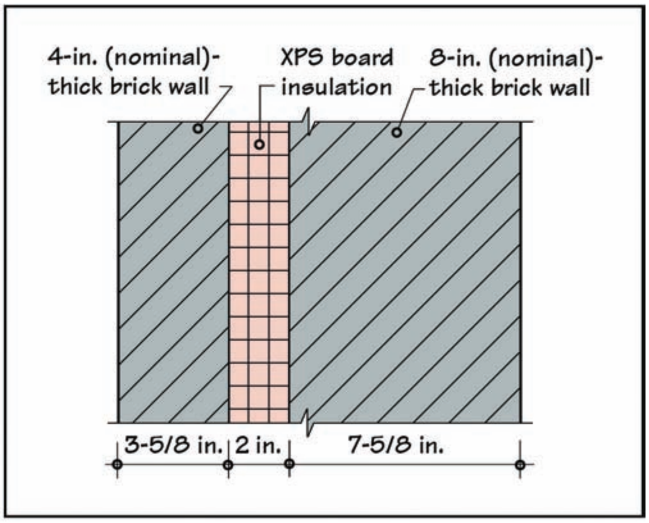

4-in. (nominal)-thick brick wall
XPS board insulation
8-in. (nominal)-thick brick wall
3-5/8 in.
2 in.
7-5/8 in.

FIGURE 5.9 A brick wall assembly with sandwiched insulation (refer to Example 5.2).

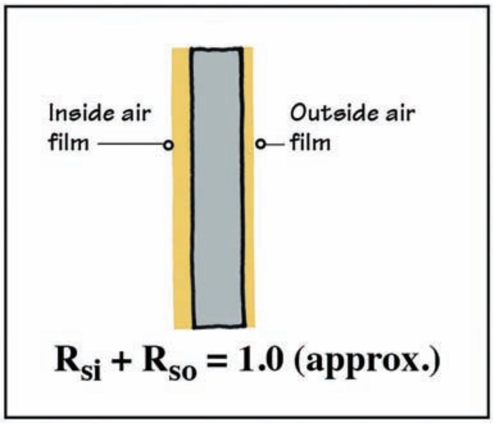


FIGURE 5.10 The inside and outside air films on the surfaces of an assembly and their R-values. The R-value of inside surface film, R_{si}, is approximately 0.7. The R-value of the outside film, R_{so}, is approximately 0.2. Therefore, $R_{si} + R_{so} = 0.9$, which may be assumed as equal to 1.0.

5.7 SURFACE RESISTANCES

In addition to the layers of solid materials comprising an assembly, there are two invisible layers that contribute to its total R-value. These layers are thin films of air of nearly zero velocity that cling to the inside and outside surfaces of an assembly, Figure 5.10. Because each air film has a certain thickness, it increases the total R-value of the assembly.

The R-value of each film is called the *film resistance* or, more commonly, the *surface resistance*. Thus, there is an inside surface resistance, R_{si}, and an outside surface resistance, R_{so}, corresponding to the inside and outside air films, respectively. Because the surface resistances are always present, Equation (5.3) is modified as follows:

$$\boxed{R_t = R_{si} + R_1 + R_2 + R_3 + \cdots + R_{so}} \qquad \textbf{Eq. (5.4)}$$

Because the inside air velocity is usually smaller than the outside air velocity, the inside film is thicker than the outside film. A good approximation of R_{si} is 0.7, and that of R_{so} is 0.2 (in the U.S. system of units). Thus, $R_{si} + R_{so}$ may be taken as approximately equal to 0.9 (or, 1.0 as a rule of thumb). Note that the total R-value of an assembly, obtained from Equation (5.4), may be rounded to the nearest whole number (integer).

Because both surface resistances provide a total R-value of only 1.0, they do not add significantly to the total R-value of a typical roof or wall assembly (see Example 5.4 later in this chapter). However, they contribute greatly to the R-value of a glazed window or a roof skylight, because a single sheet of glass has an extremely small R-value—virtually zero—as shown in Example 5.1. In fact, the total R-value of a single sheet of glass is 1.0, which is provided almost entirely by the inside and outside surface resistances (see Example 5.3).

AIR-TO-AIR HEAT TRANSFER

The inclusion of R_{si} and R_{so} implies that Equation (5.4) represents the resistance to heat flow from the outside air to the inside air, referred to as *air-to-air heat transfer*. Because we record air temperatures, it is the air-to-air heat transfer that is used in all heat-transfer calculations and energy modeling. Therefore, in referring to R-values of building assemblies, we generally imply air-to-air heat-transfer resistance, unless stated otherwise.

Example 5.3
(Estimating the R-Value of Window Glass)

Calculate the R-value of a $\frac{1}{4}$-in-thick sheet of window glass.

Solution

From Table 5.2, the ρ-value (R-value of 1-in-thick) glass sheet = 0.14. Therefore, the R-value of a $\frac{1}{4}$-in.-thick glass sheet = 0.035. With the inclusion of $R_{si} = 0.7$ and $R_{so} = 0.2$, the total R-value of the glass sheet = 0.935 (approximately 1.0).

5.8 SURFACE EMISSIVITY AND R-VALUES OF AIR SPACES

So far, we have discussed conductive heat transfer—the dominant mode in most building assemblies. The other two modes, convection and radiation, occur only in air spaces that exist in walls, roof-ceiling assemblies (attics), floor assemblies (crawl spaces), and insulating glass units. Theoretically, the concept of R-value is applicable only to solid components in which conduction is the only mode of heat transfer. However, the concept is extended to air spaces also, and an air space is assigned an R-value just like a solid component, although the primary modes of heat transfer through an air space are convection and radiation.

R-VALUE OF A VERTICAL AIR SPACE

The R-value of an air space varies with its width, the direction of heat flow, and its orientation (whether it is a horizontal or a vertical air space). For a vertical air space (wall cavity), the direction of heat flow is unimportant because it is primarily horizontal. As for the width of air space, the R-value increases with an increase in the width of the air space, up to an R-value of 1.0. This value applies to an air space $\frac{1}{2}$in. wide. Beyond a width of $\frac{1}{2}$in., the R-value of the air space does not increase. Therefore, the R-value of a vertical air space is generally assumed as 1.0, regardless of its width. This takes into account the two film resistances within the cavity and both convection and radiation heat transfers.

Note that radiation heat transfer is unaffected by the width of the air space. As long as there is a space between the two opposite surfaces of an air space, radiation heat transfer will occur between them. However, radiation heat transfer can be altered (reduced) by including a layer of metal foil within the air space, Figure 5.11. This is generally achieved by laminating an aluminum foil to one of the two surfaces of the air space, referred to as *lining the air space*.

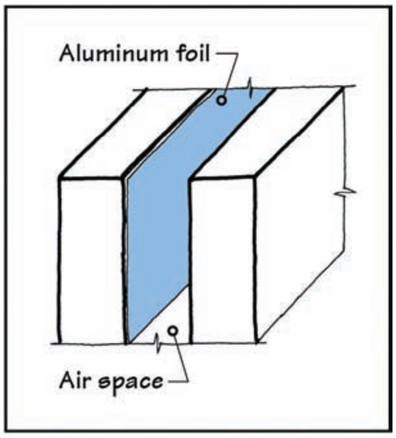


FIGURE 5.11 Radiation heat transfer through an air space is reduced if one surface of the air space is lined with bright metal, such as aluminum foil. Thus, the R-value of a lined air space is greater than that of an unlined air space (see Table 5.3).

Aluminum foil reduces radiation heat transfer due to its low *emissivity*. Emissivity is a property of the surface of an object that refers to its potential to emit radiation. In fact, the magnitude of radiation emitted by an object is directly related to its emissivity and its temperature.

The effect of temperature on the radiation emitted by an object is well known. If we place an iron rod inside a fire for a short while and then withdraw it, we can feel the heat emitted by the rod. If we place the same rod in the fire for a long time and then withdraw it, we see that it emits more heat. The increase in radiated heat is due to the rise in the temperature of the rod.

The effect of the emissivity of the object on the amount of radiation emitted by it is not as readily observed. However, if we take radiation measurements on a heated object, we will observe that it emits a certain amount of heat. If the same object is covered all around with aluminum foil, we will observe that the heat emitted by it is much less, Figure 5.12. Restaurants commonly keep a baked potato wrapped in aluminum foil so that it will emit less heat and thereby cool more slowly.* In this case, the foil reduces the emission of heat. (Note that the term *emission* is used only with radiation, not with conduction or convection.)

The emissivity of a material lies between 0 and 1. Most building materials (brick, concrete, wood, plaster, gypsum board, steel, etc.) have a high emissivity—approximately 0.90, Figure 5.13. Polished metals, on the other hand, have a low emissivity. A highly polished metal, such as stainless steel or aluminum, has an emissivity of only 0.05. This means that if an object made of brick, concrete, etc. at a certain temperature, is covered with aluminum foil, the heat emitted by it will be (0.05/0.90) = 0.06, (i.e., 6%) of the heat emitted by the same object (at the same temperature) without the foil covering.

Note that emissivity is a property of the surface, not of the bulk of the material. Thus, changing the surface characteristic of an object changes its emissivity. For instance, plywood's emissivity is nearly 0.9, but if that plywood is laminated with aluminum foil, its emissivity becomes only 0.05. Aluminum foil is the metal that is commonly used in building assemblies because of its relatively low cost.

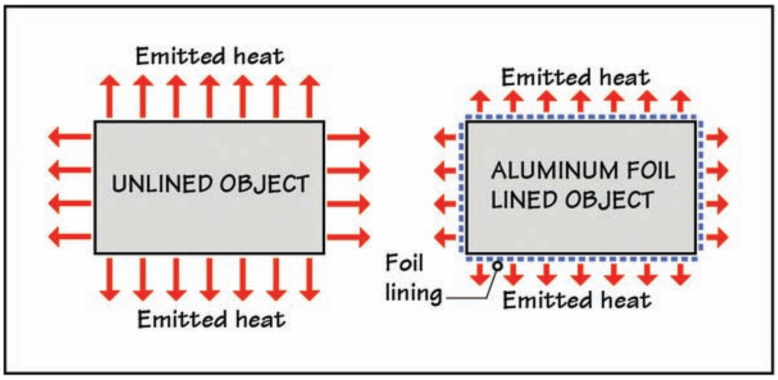


FIGURE 5.12 Radiation emitted by two objects that are at the same temperature. The objects are identical except that one of them is lined (wrapped) with aluminum foil. The unlined object emits more radiation (heat) than the one lined with aluminum foil.

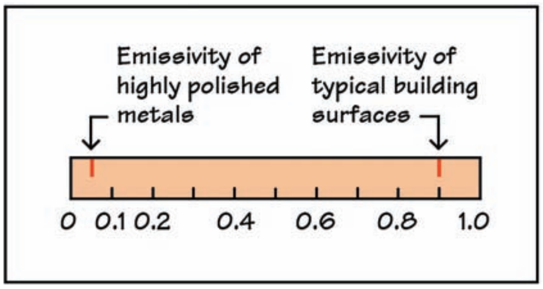

Emissivity of highly polished metals
Emissivity of typical building surfaces
0
0.1
0.2
0.4
0.6
0.8
1.0

FIGURE 5.13 Emissivity scale. The emissivity of objects varies from 0 to 1.0.

---

* The aluminum foil also helps retain the moisture within the potato.

Lining a surface of the air space with foil implies that the heat emitted by that surface is small; hence, the amount of heat transferred to the opposite surface is small. This increases the R-value of the air space. Thus, the R-value of a typical foil-lined air space in a wall is approximately equal to 2.5—an increase of 1.5 over that of an unlined air space.

LOCATION OF LOW-EMISSIVITY MATERIAL (ALUMINUM FOIL) IN A VERTICAL AIR SPACE

A fundamental fact related to emissivity is that *the emissivity of a surface is always equal to its absorptivity*.[†] Because most building surfaces have an emissivity of 0.9, their absorptivity is also 0.9, which means that they absorb 90% of the radiation falling on them. A foil-lined surface, on the other hand, absorbs only 5% of the radiation falling on it, because its absorptivity (or emissivity) is 0.05. Its reflectivity is, therefore, 0.95; that is, it reflects 95% of the radiation falling on it. That is why aluminum foil is also referred to as a *reflective insulation* or a *radiant barrier*.

This fact implies that the location of the foil in an air space—on the warmer or cooler side of the space—has a negligible effect on the R-value of the air space. Thus, in Figure 5.14, surface 1 emits a large amount of heat because its emissivity is high (equal to 0.9). When this heat falls on surface 2, most of it is reflected back because surface 2 is lined with aluminum foil with a reflectivity of 95%. Consequently, net heat transfer from surface 1 to surface 2 is reduced, increasing the R-value of the air space (in comparison with that of an unlined air space).

If surface 1 is lined with a low-emissivity material (aluminum foil), the heat emitted by it toward surface 2 is small, Figure 5.15. Therefore, the heat flow across the air space is small,

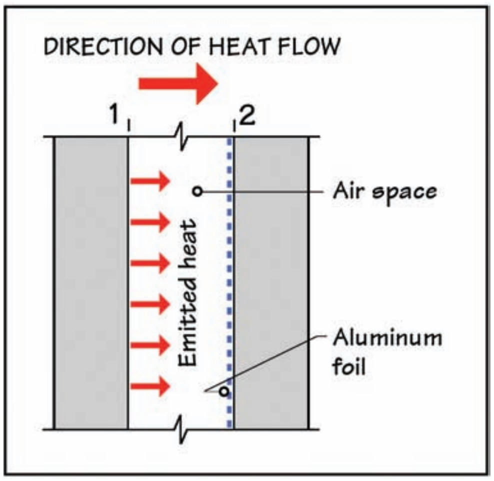


FIGURE 5.14 In this illustration, the wall on the left side of the air space is warmer than the wall on the right side. Therefore, there is net heat transfer from surface 1 of the air space to surface 2. Because surface 2 is lined with aluminum foil (with an emissivity of 0.05, i.e., a reflectivity of 95%), 95% of the heat falling on surface 2 is reflected back to surface 1, giving low heat transfer from surface 1 to surface 2, which means that the R-value of the air space is high.

If there is no foil lining on surface 2, its emissivity is 0.9 (hence, a reflectivity equal to 10%). Thus, only 10% of heat falling on surface 2 is reflected back, resulting in a relatively greater heat transfer from surface 1 to surface 2, which gives a lower R-value of the air space.

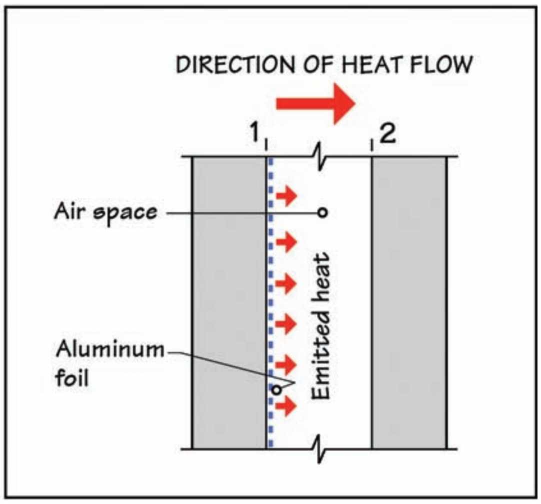


FIGURE 5.15 In this illustration also (similar to that of Figure 5.14), the wall on the left side of the air space is warmer than the wall on the right side. Therefore, there is net heat transfer from surface 1 of the air space to surface 2. However, because surface 1 is lined with aluminum foil (with an emissivity of 0.05 compared with 0.9 of an unlined surface), it emits much less heat to surface 2 as compared with the assembly of Figure 5.14. Therefore heat transfer from the left side to the right side is low, giving a high R-value for the air space.

In other words, the radiation heat transfer through a foil-lined air space is the same regardless of whether the foil is on the warmer side of the air space (as shown here) or on the cooler side, as shown in Figure 5.14.

[†] Emissivity and absorptivity of a surface are equal if the radiation falling on the object is approximately of the same wavelength as the radiation emitted by it. The wavelength of radiation emitted by an object is a function of its temperature. Because the temperature range of building surfaces is small, the equality of emissivity and absorptivity of a surface is true for all practical purposes.

TABLE 5.3 APPROXIMATE R-VALUES OF AIR SPACES

Type of air space and its dimensions			R-value
Unlined	Vertical—heat flow direction ↔	Width ≥ 0.5 in.	1.0
	Horizontal—heat flow up ↑	Width ≥ 0.5 in.	1.0
	Horizontal—heat flow down ↓	Width ≥ 0.5 in.	1.0
Aluminum foil lining on one face of air space	Vertical—heat flow direction ↔	Width ≥ 0.5 in.	2.5
	Horizontal—heat flow up ↑	Width ≥ 0.5 in.	2.0
	Horizontal—heat flow down ↓	Width = 0.5 in.	2.5
	Horizontal—heat flow down ↓	Width ≥ 1.5 in.	5.6
	Horizontal—heat flow down ↓	Width ≥ 3.5 in.	8.5

Source: Reference 5.1.

thereby increasing the R-value of the air space. Thus, in either case (Figure 5.14 or 5.15), the end result is the same.

R-VALUE OF A HORIZONTAL AIR SPACE (ATTIC)

The R-value of an attic is a function of whether the heat flow is up or down. The heat flow is up in an attic in winter time and down in summer. Because, it is easier for heat to flow up, the R-value of an attic during winter is lower than in summer, but the difference between the two values is small. On the average, R-1 is a good estimate for the R-value of an attic, regardless of its depth and the direction of heat flow (up or down), as shown in Table 5.3 [Ref. 5.1].

If an aluminum foil is used in an attic, its R-value for upward heat flow is approximately R-2, but for downward heat flow, the attic air space behaves as an R-8.5 material. In other words, the benefit of aluminum foil in attics in warm climates is substantial. Generally, the aluminum foil is laminated to the underside of roof sheathing, Figure 5.16. Table 5.3 summarizes the approximate R-values of vertical and horizontal air spaces.

5.9 SURFACE COLOR OF ENVELOPE ASSEMBLIES

In asserting that the emissivity of a building component governs the absorption or reflection of radiation that falls on it, it must be emphasized that the radiation referred to must be from a low-temperature source, such as an opposing building component or the ground. If the source of radiation is a high-temperature source, such as the sun, it is not the emissivity of the building component that governs the absorption or reflection of radiation, but the color of the building component. A light-colored component absorbs less solar radiation than a dark-colored component.

In other words, if the absorption of solar radiation by a building surface is to be reduced, the building surface should be painted with a light color, preferably white. The use of white building envelope components reduces the amount of solar radiation absorbed by the building, which reduces the cooling load on the building. The use of white-colored roofs is particularly helpful in reducing the *urban heat island effect.*

NOTE

Urban Heat Island Effect and Cool Roofs

Urban areas are generally warmer than the surrounding rural areas. This phenomenon, referred to as the *urban heat island effect*, occurs because the solar radiation is absorbed and stored by buildings, roads, and other elements of the built environment, which are generally dark in color (e.g., black asphalt roads and roofs). The corresponding rural areas are cooler because of their lighter color ground and vegetation.

According to the U.S. Environmental Protection Agency (EPA), the mean ambient air temperature of cities with 1 million people is approximately 2°F to 5.5°F higher than that of the surrounding rural areas. This difference increases substantially (up to about 22°F) in the evenings as the heat stored in the built environment is released.

If the exterior building surfaces are white in color, the heat island effect is reduced as the buildings reflect solar radiation back to the atmosphere. Consequently, the exterior surface temperatures of buildings and ground are lower, resulting in lower ambient air temperatures.

A lower air temperature reduces cooling loads on buildings, thereby conserving energy in the entire urban area. Because energy conservation helps the environment, the color of building envelope surfaces plays a critical role. As a start, therefore, the EPA is encouraging the use of white or light-colored roofs, referred to as *cool roofs*. (See the section on sustainability in Chapter 33.)

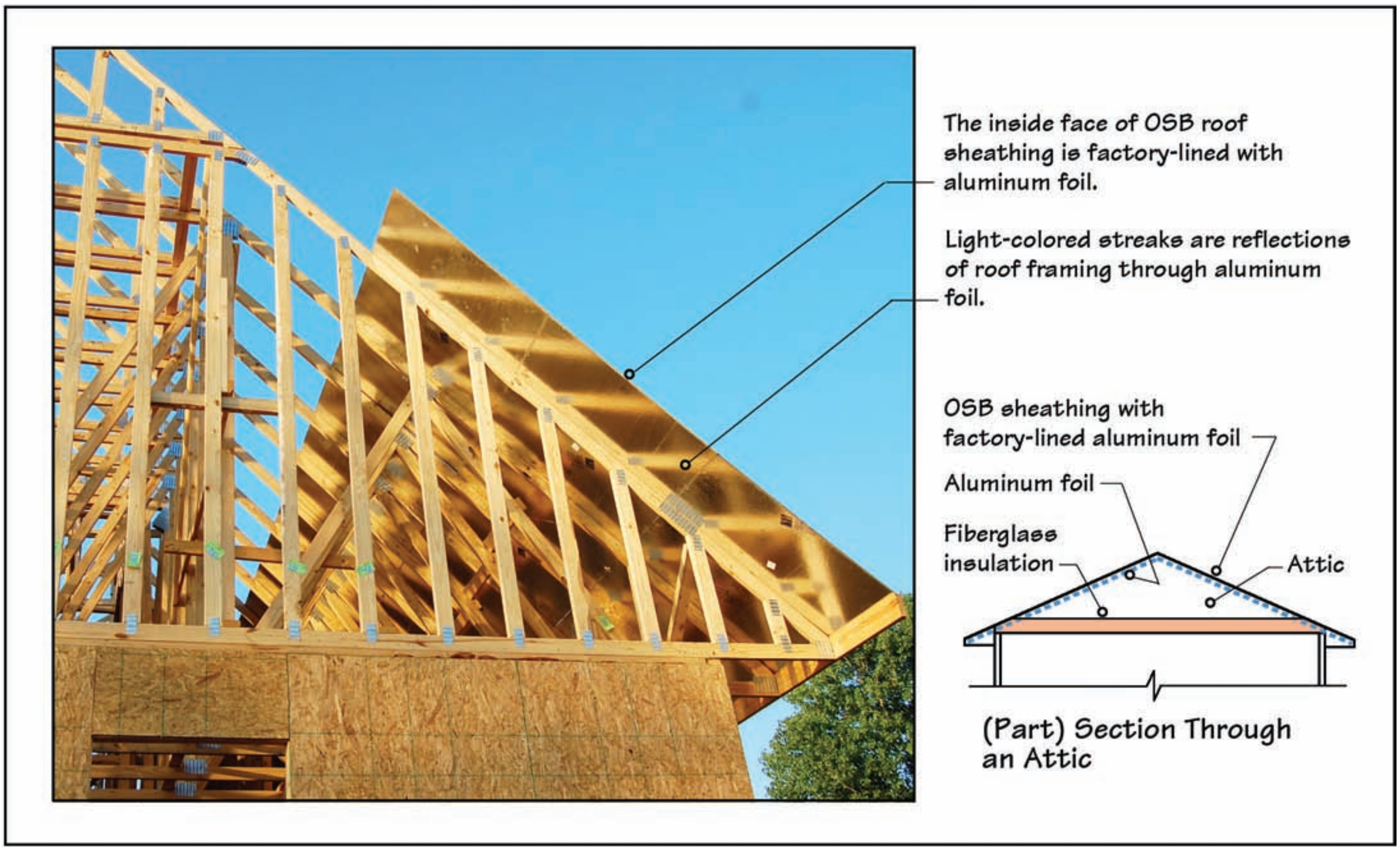

The inside face of OSB roof sheathing is factory-lined with aluminum foil.
Light-colored streaks are reflections of roof framing through aluminum foil.
OSB sheathing with factory-lined aluminum foil
Aluminum foil
Fiberglass insulation
Attic
(Part) Section Through an Attic

FIGURE 5.16 Aluminum-foil-lined OSB roof sheathing over an attic.

Example 5.4
(R-Value of a Wall with an Air Space)

Determine the R-value of a wall consisting of 2 × 41 (actual dimensions $\frac{1}{2}$ in. × 3$\frac{1}{2}$ in.) wood studs spaced 16 in. on center. The spaces between the studs are filled with 3$\frac{1}{2}$-in.-thick fiberglass insulation. Other members of the wall are shown in Figure 5.17.

Solution

The R-values of various layers of the assembly are tabulated below.

Element	R-value
Inside surface resistance	0.7
$\frac{1}{2}$-in.-thick gypsum	0.5(0.60) = 0.3
3$\frac{1}{2}$-in.-thick fiberglass insulation	3.5(3.5) = 12.25
0.5-in.-thick oriented strand board, OSB	0.5(1.4) = 0.7
2-in.-wide air space (Table 5.3)	1.0
3$\frac{5}{8}$-in.-thick brick veneer	3.625(0.2) = 0.73
Outside surface resistance	0.2

$$R_t = 0.7 + 0.3 + 12.25 + 0.7 + 1.0 + 0.73 + 0.2 = 15.88$$

In other words, this wall assembly is an R-16 assembly.

Note that in the preceding calculations, we have ignored the presence of wood studs and assumed that the space occupied by the studs is occupied by fiberglass insulation. Because the R-value of wood studs is lower than that of fiberglass, the actual R-value of the assembly is, in fact, less than 15.88. A more precise method of determining the R-value of an assembly in which there are two or more materials in the same layer of the assembly is explained in Example 5.5.

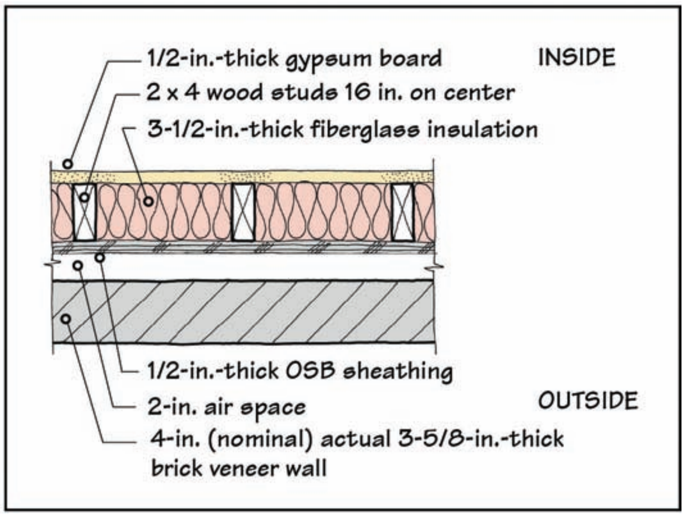

1/2-in.-thick gypsum board
INSIDE
2 x 4 wood studs 16 in. on center
3-1/2-in.-thick fiberglass insulation
1/2-in.-thick OSB sheathing
OUTSIDE
2-in. air space
4-in. (nominal) actual 3-5/8-in.-thick brick veneer wall

FIGURE 5.17 A brick-veneer, wood stud wall (in plan); refers to Example 5.4.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

18. The R-value of a single glass sheet, without considering the film resistances, is approximately

a. 4.0.
b. 3.0.
c. 2.0.
d. 1.0.
e. 0.

19. The R-value of a single glass sheet, including the film resistances, is approximately

a. 4.0.
b. 3.0.
c. 2.0.
d. 1.0.
e. 0.

20. The emissivity of a material lies between

a. 0 and 1.
b. 1 and 2.
c. 1 and 10.
d. 0 and 100.
e. none of the above.

21. Which of the following materials has the smallest value of emissivity?

a. Fiberglass
b. Highly compressed fiberglass
c. Metal
d. Highly polished metal
e. All of the above have the same value of emissivity

22. Aluminum foil is commonly used in building assemblies because it

a. lowers heat transfer due to conduction.
b. lowers heat transfer due to convection.
c. lowers heat transfer due to radiation.
d. lowers heat transfer due to conduction as well as convection.
e. lowers heat transfer due to convection as well as radiation.

23. Like color, emissivity is a property of the surface of the material, not of the entire body of the material.

a. True
b. False

24. The R-value of a building assembly is influenced by the inside and outside air films. The sum of the R-values of these two films ($R_{si} + R_{so}$) is approximately equal to

a. 0.1.
b. 5.0.
c. 10.0.
d. 1.0.
e. none of the above.

25. The approximate R-value of an air space in a wall is

a. R-1.
b. R-1.5.
c. R-2.0.
d. R-2.5.
e. none of the above.

26. The approximate R-value of an air space in a wall with an aluminum foil lining is

a. R-1.
b. R-1.5.
c. R-2.0.
d. R-2.5.
e. none of the above.

27. When an aluminum foil is used in attic spaces, it is

a. laminated to ceiling gypsum board.
b. laminated to fiberglass insulation.
c. sandwiched between ceiling gypsum board and fiberglass insulation.
d. laminated to outside-facing surface of roof sheathing.
e. laminated to inside-facing surface of roof sheathing.

28. The use of aluminum foil in attics is more useful in warm climates than in cold climates.

a. True
b. False

5.10 MULTILAYER ASSEMBLY IN PARALLEL COMBINATION—THE U-FACTOR

The thermal property of an assembly, which is related directly to heat flow through a building assembly, is called its *thermal transmittance* or *U-value*. The U-value is the reciprocal of the R-value. In practice, we are concerned with the air-to-air heat transmittance through a wall or roof. Hence, the U-value includes the inside and outside surface resistances, R_{si} and R_{so}. Thus, the U-value of an assembly is given by

$$\boxed{U = \frac{1}{R_{si} + R_1 + R_2 + R_3 + \cdots + R_{so}}} \qquad \textbf{Eq. (5.5)}$$

If the total resistance of an assembly, including the inside and outside film resistances, is 10.0, its U-value is $1/10.0 = 0.10$. Architects and engineers compare the effectiveness of different assemblies in terms of their U-values. The U-value of an assembly can be calculated by first calculating R_t and then finding its reciprocal. Thus, the U-value of the wall assembly of Example 5.4 is $1/15.88 = 0.063$. The greater the U-value of an assembly is, the greater is the heat flow through it, and vice versa.

The real usefulness of U-value, however, lies in heat-transfer calculations, because heat transfer is directly proportional to the U-value. Thus, if Q denotes the amount of heat transmitted through the assembly in 1 h (Btu/h), A denotes the area of the assembly, and Δt is the difference between the inside and the outside air temperatures, then:

$$\boxed{Q = U\,A\,(\Delta T)} \qquad \textbf{Eq. (5.6)}$$

Therefore, U is called *air-to-air thermal transmittance*, and its unit of measurement is Btu per hour, per sq ft, per °F, that is, Btu/(h-ft^2-°F).

ASSEMBLY IN PARALLEL COMBINATION AND ITS U-FACTOR

The assembly of Figure 5.8 consists of several layers that are arranged such that the heat flow through each layer is the same. In such an assembly, the layers are said to be in series

NOTE

U-Value as Air-to-Air Thermal Transmittance

Note that the U-value of an assembly includes the effect of internal and external surface resistances. Therefore, it is used in determining the heat transmitted through the assembly from the inside air to the outside air, or vice versa.

NOTE

Difference Between U-Value and U-Factor

The terms, U-value and U-factor, refer to essentially the same concept, but in this text, we use the term U-value for an individual assembly, such as an opaque part of a wall, a window, a door, roof, skylight, and so on. Where an assembly consists of multiple parts arranged side-by-side (horizontally or vertically), as shown in Figures 5.18 and 5.20, the overall U-value of such an assembly has been termed as the U-factor, designated by the symbol U_o.

combination. If the layers are arranged side-by-side (either horizontally or vertically), as shown in Figure 5.18, the combination is referred to as the *parallel combination*. A typical example of an assembly in parallel combination is an exterior wall with opaque parts, glazed windows, and doors. The doors and windows usually have a lower R-value than the opaque part(s) of the wall. Similarly, a roof may have skylight(s). So, how do we obtain the overall R-value of such assemblies?

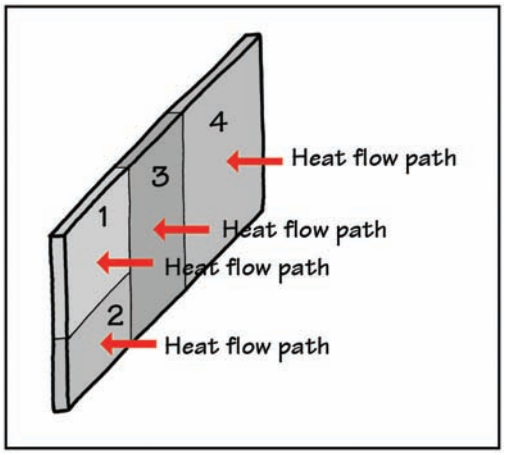


FIGURE 5.18 The heat flowing through an assembly, with several parts arranged side-to-side, divides itself into parallel paths. The heat flow through each path is not the same, in contrast with the assembly in series combination of Figure 5.8.

The determination of the overall R-value of an assembly (in parallel combination) is simplified if we consider the U-values of the individual parts rather than their R-values. Consider a wall that consists of several parts with different U-values, as shown in Figure 5.18. As the heat flows through such an assembly, it divides itself into parallel paths. One heat-flow path goes through part 1, another path through part 2, and so on. The heat flow through each part is different. If the U-values of various parts are $U_1, U_2, U_3, \ldots$, it can be shown that the overall U-value, U_o, of the entire wall assembly is given by:

$$\boxed{U_o = \frac{A_1 U_1 + A_2 U_2 + A_3 U_3 + \cdots}{A_1 + A_2 + A_3 + \cdots}} \qquad \textbf{Eq. (5.7)}$$

Where, $A_1, A_2, A_3, \ldots$, are the respective areas of parts 1, 2, 3, . . ., of the assembly.

We will call the overall U_o-value as the *U-factor* of the assembly, to distinguish it from the U-values of its individual parts.

The overall R-value of the assembly, R_o, is

$$\boxed{R_o = \frac{1}{U_o}} \qquad \textbf{Eq. (5.8)}$$

Example 5.5
(U-Value of the Wall Assembly of Example 5.4)

Determine the U-value of the wall assembly of Example 5.4 by determining the precise R-value of the stud-fiberglass layer, redrawn in Figure 5.19.

Solution

The studs and fiberglass are in parallel combination. Therefore, we will first determine the overall U-value of the stud-fiberglass layer. Because the studs are spaced 16 in. on center, the width of the fiberglass insulation in each stud space is 14.5 in., and the width of a stud is 1.5 in.

Using Table 5.2, the R-value of 3.5-in.-thick fiberglass is 3.5(3.5) = 12.25. Hence, its U-value is 0.082.

Similarly, the R-value of (3.5-in.-deep) wood stud is 1.2(3.5) = 4.2. Hence, its U-value is 0.24.

From Figure 5.19, the U-value of the stud-fiberglass layer can be obtained by considering only one stud space consisting of 14.5-in.-wide fiberglass insulation plus the 1.5-in.-wide wood stud. From Equation (5.7), the overall U-value of stud-fiberglass layer is:

$$U_o = \frac{14.5(0.082) + 1.5(0.24)}{(14.5 + 1.5)} = 0.097$$

From Equation (5.8),

$$R_o = \frac{1}{0.097} = 10.31$$

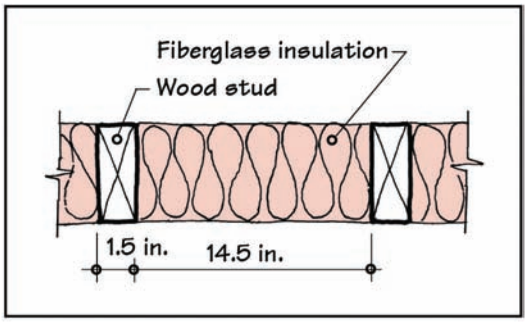


FIGURE 5.19 Stud-fiberglass layer of Example 5.4; refer to Example 5.5.

In other words, the R-value of the stud-fiberglass layer, which we had assumed as 12.25 in Example 5.4, is, in fact, 10.31. Note that the decrease in R-value is due to thermal bridging caused by the studs. If the wood studs are replaced by metal studs, thermal bridging will be more pronounced, further reducing the overall R-value of the stud-fiberglass layer. Hence, a more precise total R-value of the wall assembly of Example 5.4 (which takes into account thermal bridging through studs) is not R-16 but R-14, as shown below:

$R_t = 0.7 + 0.3 + 10.31 + 0.7 + 1.0 + 0.73 + 0.2 = 13.94$, i.e., R-14

The U-value of the assembly of Figure 5.17 = 1/13.94 = 0.072

Example 5.6

(U-Factor of the Wall Assembly of Figure 5.20)

Determine the U-factor of the wall assembly of Figure 5.20. The overall dimensions of the wall are 20 ft × 12 ft. The opaque part of the wall is composed of wood studs and brick veneer of Figure 5.17, whose U-value is 0.072, as shown in Example 5.5.

The window areas are 20 ft^2 and 25 ft^2. Assume that their U-values are 1.0 and 0.7, respectively. The door area is 35 ft^2, and its U-value is 0.3.

Solution

Opaque wall area = [(20 × 12) − (20 + 25 + 35)] = 160 ft^2. Its U-value is 0.072.

Window area = 20 ft^2. Its U-value is 1.0.
Window area = 25 ft^2. Its U-value is 0.7.
Door area = 35 ft^2. Its U-value is 0.3.

From Equation (5.7), the overall U-value (i.e., the U-factor) of the wall is

$$U_o = \frac{160(0.072) + 20(1.0) + 25(0.7) + 35(0.3)}{240} = 0.248$$

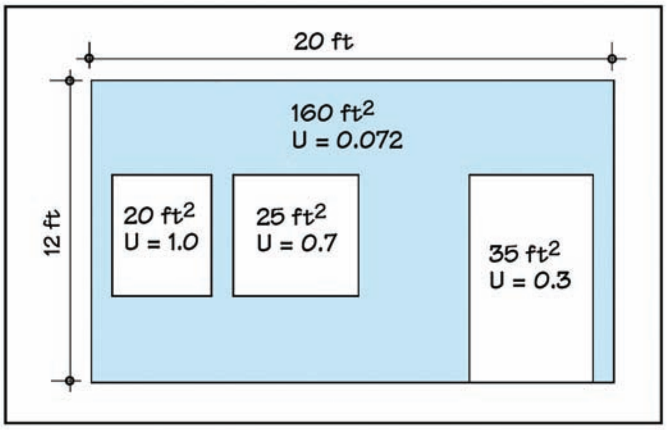

20 ft
160 ft²
U = 0.072
12 ft
20 ft²
U = 1.0
25 ft²
U = 0.7
35 ft²
U = 0.3

FIGURE 5.20 Wall assembly of Example 5.6.

Because the U-factor of the assembly is 0.248, its overall R-value is:

$$R_o = \frac{1}{0.248} = 4.03$$

Observe that although most of the wall (160 ft^2 out of a total of 240 ft^2) has an R-value of 13.94 (i.e., R-14), the overall R-value of the assembly has been degraded to R-4 because of the presence of parts with low R-values.

Example 5.7

(U-Factor of the Ground Floor Assembly Over a Crawl Space)

Determine the U-factor of the ground floor assembly of Figure 5.21 consisting of 2 × 12 [actual dimensions ($1\frac{1}{2}$ in. × $11\frac{1}{4}$ in.)] wood joists spaced 24 in. on center. The spaces between joists are filled with $11\frac{1}{4}$-in.-thick fiberglass insulation, whose effective R-value (considering the effect of wood floor joists) is R-30. Other members of the floor are shown in Figure 5.21.

Solution

The R-values of various layers of the assembly are tabulated here.

Element	R-value
Inside surface resistance	0.7
1-in.-thick OSB subfloor	1.0(1.4) = 1.4
Fiberglass insulation and joist layer	30.0
Crawl space air (Table 5.3)	1.0

$$R_t = 0.7 + 1.4 + 30.0 + 1.0 = 33.1$$

Therefore, the U-factor of the assembly $= \frac{1}{33.1} = 0.030$.

Note that in the preceding calculations, we have not included: (a) the outside surface resistance because it is a part of the crawl space air, and (b) vapor retarder just below the subfloor because, being extremely thin, its R-value is virtually zero.

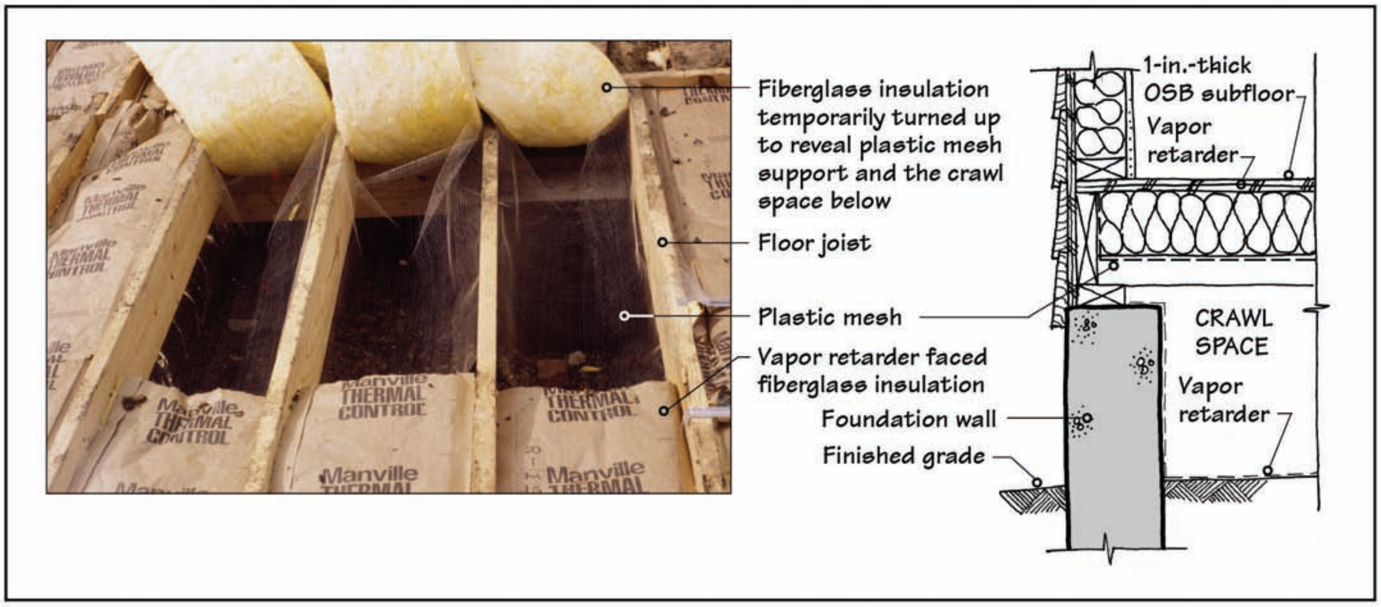

Fiberglass insulation temporarily turned up to reveal plastic mesh support and the crawl space below
Floor joist
Plastic mesh
Vapor retarder faced fiberglass insulation
Foundation wall
Finished grade
1-in.-thick OSB subfloor
Vapor retarder
CRAWL SPACE
Vapor retarder

FIGURE 5.21 Insulation in a ground floor over crawl space, refer to Example 5.7.

5.11 THERMAL BRIDGING

Example 5.6 shows that the overall R-value of an assembly is governed mainly by the part(s) that have low R-value(s). This phenomenon, known as *thermal short circuiting* or *thermal bridging,* can be further investigated by considering an assembly of two parts—A and B. Let the total area of both parts be 100 ft^2. Let part A of the assembly, with an area of 90 ft^2, have an R-value of 10.0 (U-value = 0.1). Let the area of part B be 10 ft^2 with an R-value of 1.0 (U = 1.0), Figure 5.22. Using Equation (5.7), we obtain the U-factor of such an assembly as 0.19, so that its overall R-value is 5.3:

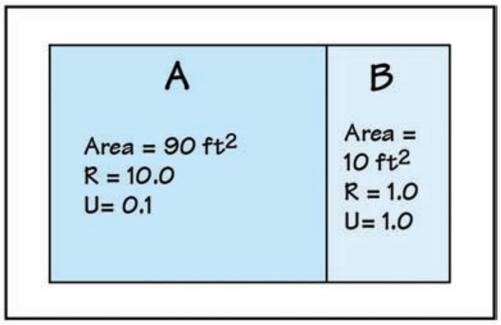


FIGURE 5.22 A two-part assembly with different areas and U-values. The total area of assembly = 100 ft^2.

$$U_o = \frac{90(0.1) + 10(1.0)}{100} = 0.19. \text{ Hence, } R_o = \frac{1}{0.19} = 5.3$$

If we now increase the R-value of part A to 20 (U = 0.05), keeping part B as before, the overall R-value of the assembly becomes 6.9, an increase of 23% from the earlier value of $R_o = 5.3$, per the following calculations.

$$U_o = \frac{90(0.05) + 10(1.0)}{100} = 0.145. \text{ Hence, } R_o = \frac{1}{0.145} = 6.9$$

A further increase in the R-value of part A to 30 (U = 0.033) changes the overall R-value of the assembly to 7.7—an increase of 12%.

This example shows that the overall R-value of the assembly is dictated by the part that has a low R-value. It further shows that increasing the R-value of a part that already has a high R-value gives diminishing returns. This fact highlights the importance of eliminating or reducing thermal bridges in the envelope. In practical terms, it means that windows and skylights function as efficient thermal bridges in the envelope because of their low R-values. Therefore, their areas should be limited, or their R-values should be high.

Another example of thermal bridging is an insulated cold-formed steel (CFS) stud wall assembly. Here, the studs function as thermal bridges. Thermal bridging through wood studs is generally small (see Example 5.5) and may be ignored for moderate climate regions. However, it is significant through steel studs, Figure 5.23(a). This is generally countered by covering the metal studs on the outside with an insulating foam (XPS or ISO board) sheathing (see Section 20.11). Similar thermal bridging occurs in concrete masonry walls, where the webs of a concrete masonry unit function as thermal bridges, Figure 5.23(b).

5.12 F-FACTOR AND C-FACTOR

While U-factor is used for heat transmission through assemblies exposed to air on both sides, such as above-ground walls, doors, windows, roofs, floors over crawl space, and so on, F-factor and C-factor are used for assemblies that are exposed to ground on one side and air on the other side, such as concrete slabs-on-ground (also called *slabs-on-ground*), and below-ground walls (e.g., basement walls). The F-factor is used for slabs-on-ground and the C-factor for below-ground walls.

CONCRETE SLAB-ON-GROUND AND THE F-FACTOR

Heat loss from a concrete slab-on-ground can be significant during cold weather (or cold climates) because of the large difference between the ground temperature and the inside air temperature. On the other hand, the difference between the ground temperature and the inside air temperature during warm weather (or in warm climates) is generally small. Therefore, we only deal with heat loss through a slab, not the heat gain. In other words, concrete

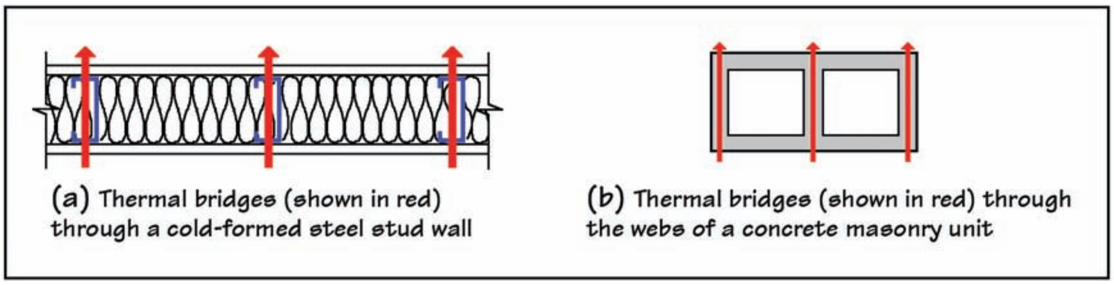

(a) Thermal bridges (shown in red) through a cold-formed steel stud wall
(b) Thermal bridges (shown in red) through the webs of a concrete masonry unit

FIGURE 5.23 Thermal bridges in cold-formed steel wall and concrete masonry units.

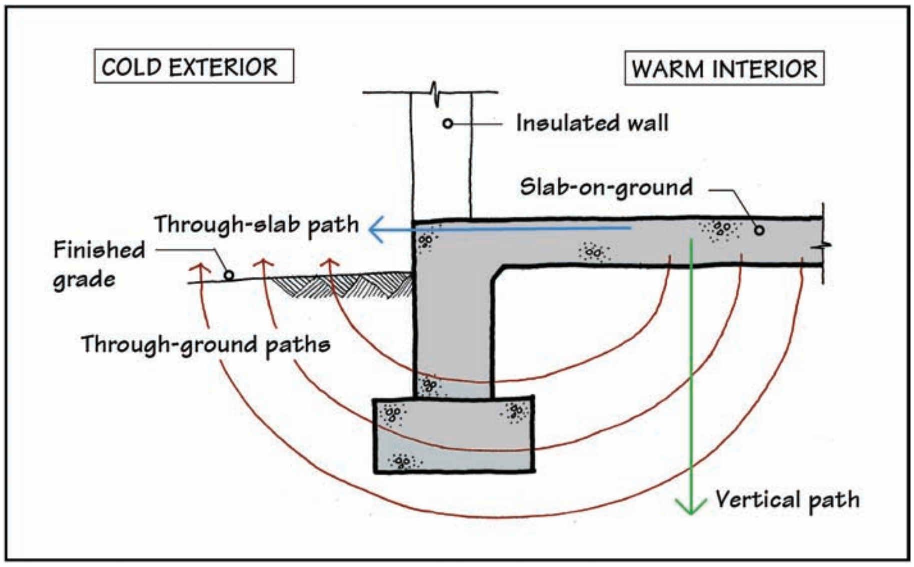


FIGURE 5.24 Various heat-flow paths through a slab-on-ground (also called slab-on-grade).

slabs-on-ground in cold climates need to be insulated, while those in warm climates do not need any insulation.

From Equation (5.1) we see that the heat flow through an assembly is a function of L (the length of heat-flow path) and ρ (resistivity of the path through which heat flows). The longer the path is, the smaller is the amount of heat flow, and vice versa. With respect to a concrete slab-on-ground, a simplified visualization of heat flow is illustrated in Figure 5.24, which shows that there are three possible paths along which heat may flow:

1. Vertical path through the thickness of the slab and into the ground
2. Horizontal path through the slab
3. Through-the-ground paths (shown by the curved lines in Figure 5.24)

Because the ρ-value of both concrete and soil are approximately equal, the parameter that affects heat flow through a slab is the path length, L. The vertical path in Figure 5.24 represents an extremely long path and, therefore, it offers large resistance to heat flow, implying insignificant heat loss in the vertical direction. Heat losses through the other two paths (horizontally through the slab, and curved paths through the soil) are functions of their respective lengths.

Because the region of the slab away from an exposed edge has long path lengths, its contribution to heat loss is small. Therefore, most of the heat loss occurs from the region that is close to the exposed edges of the slab. In other words, a slab-on-ground can be adequately insulated around its exposed perimeter. Insulating under the entire slab, in place of the exposed perimeter, yields small benefit relative to the amount of insulation used.

The standard practice, therefore, is to insulate under the slab with either horizontal or vertical insulation or a combination of both at its exposed edges. Vertical insulation is generally preferred because it does not have to bear the weight of the slab, and is easier to install. Two commonly used details for insulating a slab-on-ground with vertical insulation are shown in Figures 5.25 (a) and (b). In both details, the location of the insulation is meant to insulate the horizontal and curved heat flow paths.

The thermal property that includes the combined effect of: (a) the R-value of the insulation and (b) the depth of insulation below the ground, is called the *F-factor* of the slab-on-ground. The F-factor represents the heat loss in Btu/(h-ft-°F). The greater the F-factor, the greater the heat loss through the slab. The International Energy Conservation Code provides maximum permissible values of F-factors as a function of climate zones [Ref. 5.2]. (Climate zones are described in Section 5.14.)

The F-factor for commonly used R-values of vertical insulation are shown in Figure 5.26. Also shown are the F-factors for a fully insulated slab, that is, the slab that is provided with horizontal insulation under the entire area of the slab [Ref. 5.3].

Note from Figure 5.26 that the F-factor for a fully insulated slab with R-5 insulation is 0.46, which can be achieved by 36-in-deep, R-25 insulation placed around the exposed edges of the slab—a far more economical alternative. To expand on the point, assume a 100 ft × 100 ft slab that is exposed on its entire perimeter. The amount of exposed-edge

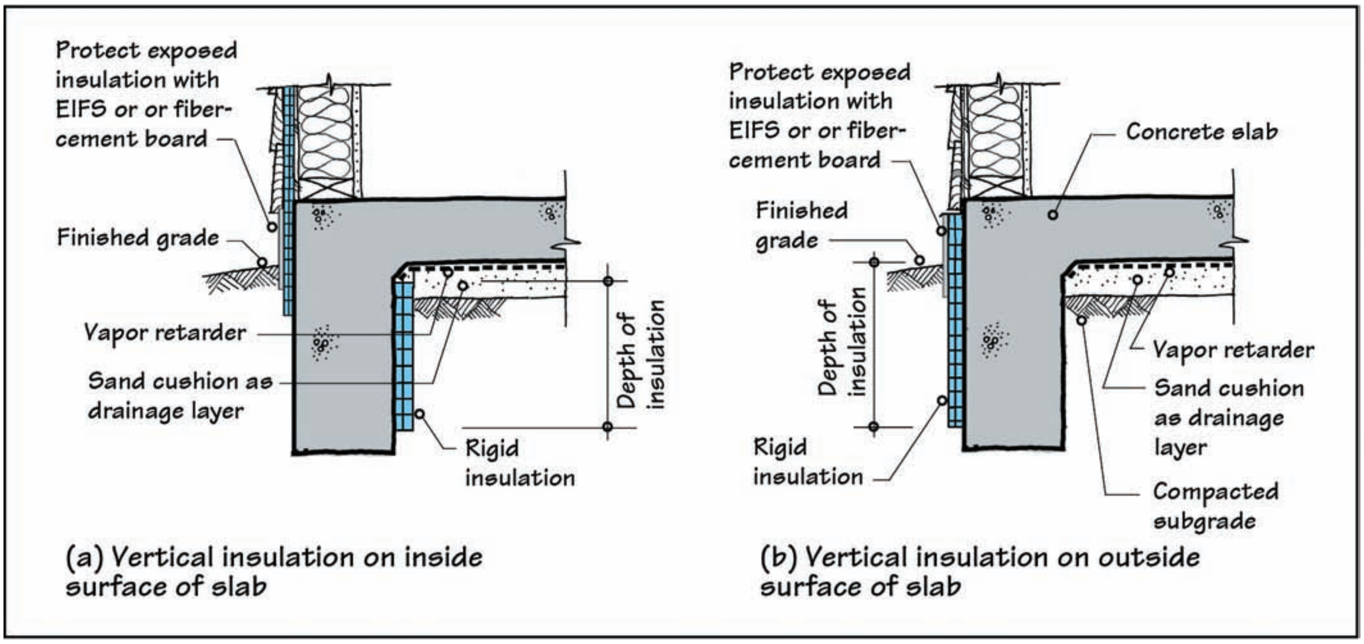

Protect exposed insulation with EIFS or or fiber-cement board
Finished grade
Vapor retarder
Sand cushion as drainage layer
Rigid insulation
Depth of insulation
(a) Vertical insulation on inside surface of slab
Protect exposed insulation with EIFS or or fiber-cement board
Concrete slab
Finished grade
Depth of insulation
Vapor retarder
Sand cushion as drainage layer
Rigid insulation
Compacted subgrade
(b) Vertical insulation on outside surface of slab

FIGURE 5.25 Two alternative details of insulating a concrete slab-on-ground with vertical insulation on its exposed edges.

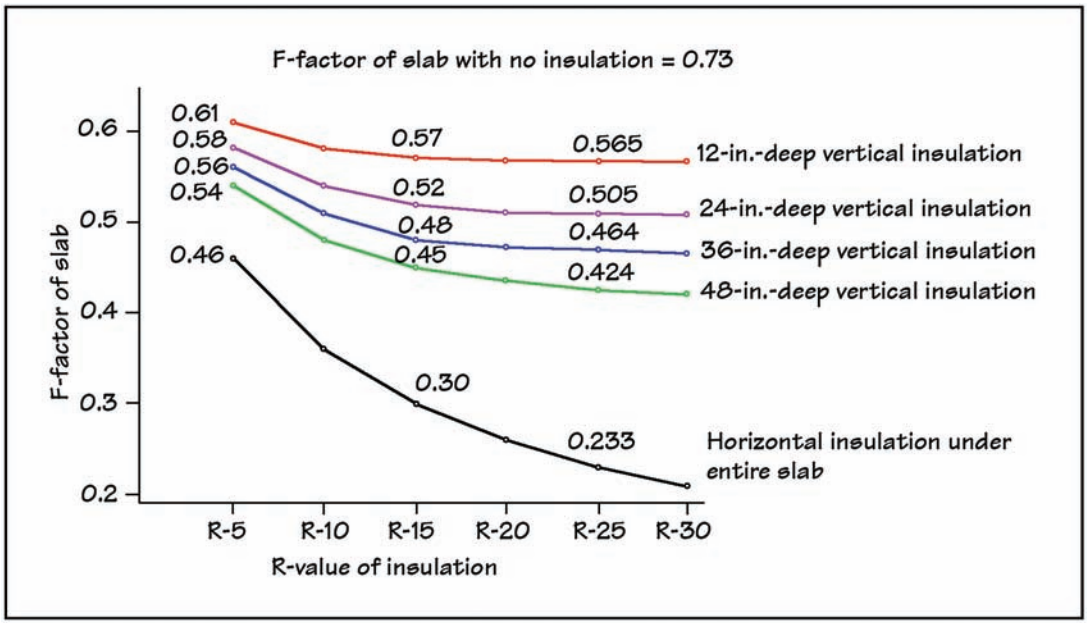


FIGURE 5.26 F-factors of a concrete slab-on-ground as a function of the R-value and depth of vertical insulation [Ref. 5.3].

insulation required is 400 ft long, 3 ft deep, that is, 1,200 ft^2, R-25 insulation. The amount of insulation required under the entire slab is 100 ft × 100 ft = 10,000 ft^2, R-5 insulation—a great deal more insulation.

BELOW-GROUND WALLS AND THE C-FACTOR

The walls of a heated basement generally consist of: a portion that is above ground and a portion that is below ground. Heat transfer through the above-ground portion (with air on both sides of the wall) is determined by the wall's U-factor. Heat transfer through below-ground portion is determined by the wall's C-factor.

C-factor is primarily a function of the R-value of the continuous insulation used in the wall. The contribution of the structural part of the wall (concrete or concrete masonry) is relatively small because the R-value of a typical basement masonry or concrete wall is approximately 1.0. Thus, a rough estimate of the C-factor of a below-ground wall is obtained from:

$$C = \left(\frac{1}{R_t}\right), \text{ where } R_t = \text{total R-value of the wall.}$$

Thus, if a below-ground wall is insulated with R-10 continuous insulation, R_t is approximately equal to 11.0, and hence, its C-factor is approximately 0.09. Note that the C-factor does not include film resistances or the effect of the soil.

Because the ground temperature reaches a constant value below a certain depth (a year-round average of the outside air temperature), the heat loss through a below-ground wall reduces with increasing depth. Therefore, the building codes require a basement wall to be insulated only up to 10 ft below the finished ground or to the level of the basement floor, whichever is smaller. The International Energy Conservation Code gives the maximum permissible values of C-factors as a function of climate zones [Ref. 5.2].

5.13 U-FACTOR, F-FACTOR, AND C-FACTOR—A SUMMARY

All three properties are effectively the heat-transfer coefficients of different parts of the envelope assembly. The smaller their values are, the smaller is the heat transfer through the assembly. U-factor applies to an envelope assembly that has air on both its surfaces—inside and outside surfaces. Therefore, it applies to both the opaque parts as well as the glazed parts of the roof, all above-ground walls, and a floor (if the floor separates a conditioned space from an unconditioned space).

F-factor and C-factor apply only to the opaque parts of the envelope. F-factor applies to a slab-on-ground and C-factor applies to the below-ground walls. The heat flow through an assembly, defined by U-factor or C-factor is given by:

$$Q = (\text{U-factor or C-factor})(A)(\Delta T)$$

Where,

Q = amount of heat flow through the assembly in unit time (Btu/h).

A = area of the assembly, for example, a wall, floor, or roof (ft^2)

ΔT = difference between the outside air temperature and the inside air temperature (°F)

For a slab-on-ground, the corresponding relationship is:

$$Q = (\text{F-factor})(L)(\Delta T)$$

Where,

Q = amount of heat flow through the component in unit time (Btu/h).

L = exposed perimeter of slab-on-ground

ΔT = as previously defined

From the above, the unit of measurement of U-factor and C-factor is Btu/(h-ft^2-°F). The unit of measurement of F-factor is Btu/(h-ft-°F).

5.14 WHERE AND HOW MUCH TO INSULATE—THE BUILDING THERMAL ENVELOPE

The discussion of thermal properties presented so far leads to two questions. Question 1: which parts of the building should be insulated, Question 2: how much insulation should be used in them? The answer to Question 1—where to insulate—is obvious: the insulation is required only in those components of the building through which heat flow would occur.

BUILDING THERMAL ENVELOPE

The heat flow in building occurs through the following components:

- Interior components, for example, a wall, floor, or a ceiling between a conditioned and an unconditioned space.
- Exterior components, that is, all above-ground components exposed to the outside.
- Below-ground components, for example, basement walls, basement slabs, and concrete slabs-on-ground.

All three component types constitute what is referred to as the *building thermal envelope*, as shown in color in Figure 5.27. Note that the term "building thermal envelope" is not the same as the commonly used term "building envelope".

AMOUNT OF INSULATION REQUIRED

The amount of insulation required is a function of two factors: (a) economics and sustainability concerns and (b) the climate of the location.

NOTE

Properties of Below-Ground Insulation

Insulation exposed to the ground, such as in basement and crawl-space walls and under slabs-on-ground, must be rigid and have a closed-cell structure. As shown in Figure 5.6, XPS and ISO meet both requirements. Their closed-cell structure helps to resist water absorption, which is necessary so that they retain their insulating efficacy. (Remember, water is a poor thermal insulator.) Of the two insulations (XPS and ISO), XPS is much better as below-ground insulation because it does not have facers, which ISO has (see Section on "Foamed Insulation" in Principles in Practice at the end of this chapter). Facers degrade because of below-ground water, and attract termites.

Another required property of below-ground insulation is termite resistance. XPS and ISO, being soft, are subjected to termite degradation because termites bore through them (but do not consume the foam as food). Boron-treated XPS and ISO are available and are claimed by their manufacturers to be termite resistant (independent and fully tested endorsement not readily available). Another termite-resistant insulation is cellular glass (see Principles in Practice at the end of this chapter). Cellular glass derives its termite-resistant property from its high compressive strength so that termites are unable to bore through it.

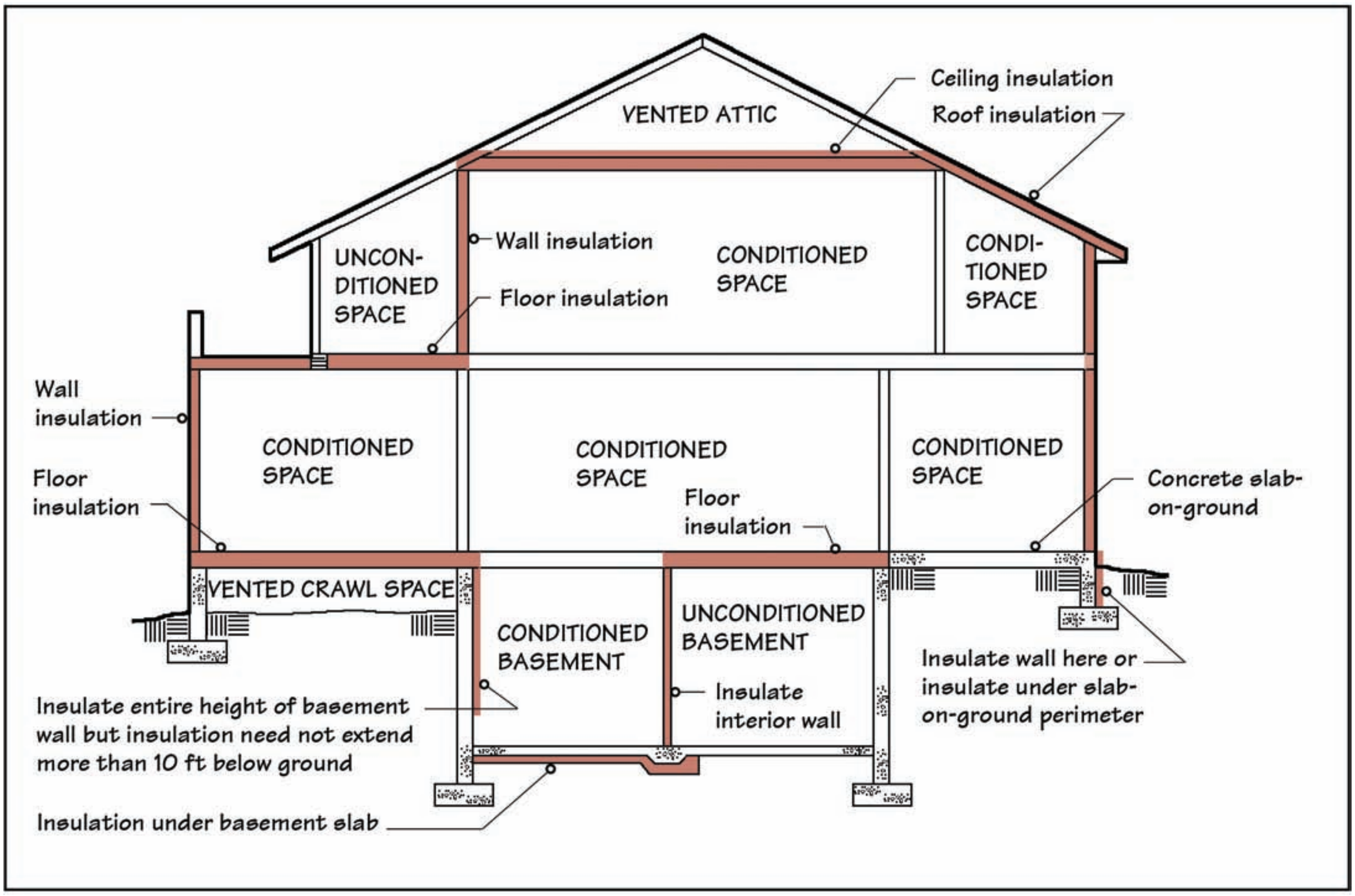

VENTED ATTIC
Ceiling insulation
Roof insulation
UNCON-DITIONED SPACE
Wall insulation
Floor insulation
CONDITIONED SPACE
CONDI-TIONED SPACE
Wall insulation
Floor insulation
CONDITIONED SPACE
CONDITIONED SPACE
CONDITIONED SPACE
Floor insulation
Concrete slab-on-ground
VENTED CRAWL SPACE
CONDITIONED BASEMENT
UNCONDITIONED BASEMENT
Insulate interior wall
Insulate wall here or insulate under slab-on-ground perimeter
Insulate entire height of basement wall but insulation need not extend more than 10 ft below ground
Insulation under basement slab

FIGURE 5.27 Location of insulation in a typical building with (thermally) conditioned and unconditioned spaces. Insulated components have been colored, and they define the "thermal envelope" of the building as per the International Energy Conservation Code (IECC).

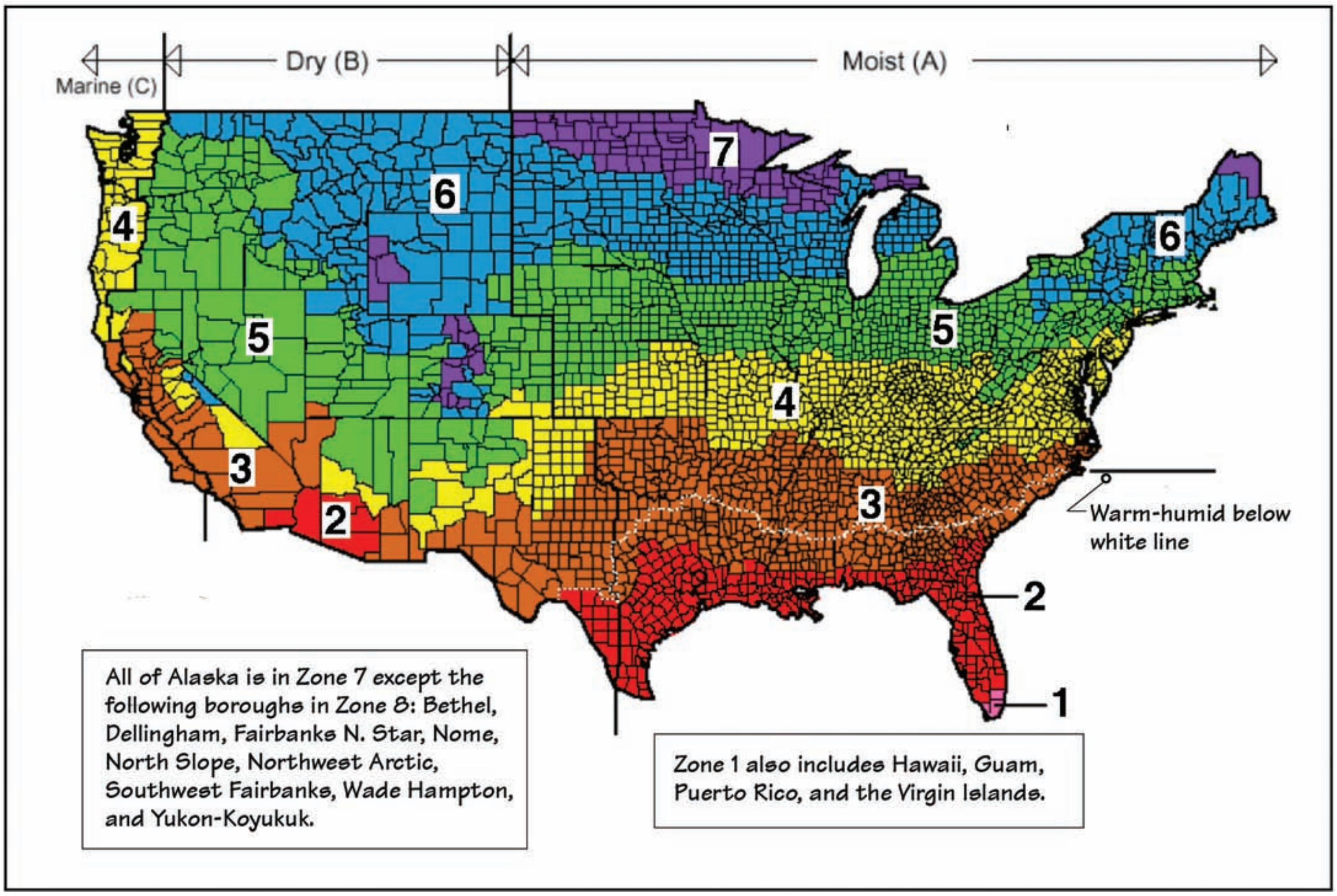
Economics and sustainability: From a purely economic standpoint, the amount of insulation required in the envelope is a function of the price of energy and the cost of providing and installing the insulation. If energy prices are low, the cost of heating and/or cooling a building is low. In that case, a lower level of insulation is economical. On the other hand, if energy prices are high, a greater amount of insulation is justified. This is precisely why the levels of insulation in buildings increased after the abrupt rise in world energy prices in 1973. A more important role of insulation is to improve the sustainability of buildings because increased levels of insulation conserves energy in heating and cooling of buildings, thereby reducing air pollution, global warming, and the buildings' carbon footprints (see Chapter 10).

Climate of the location: Climate affects the insulation requirement in the following way. In a severe climate, a greater amount of insulation is needed than in a moderate climate. In a temperate climate, little or no insulation may be required.

From the standpoint of energy use in buildings, the climate of a location is defined by two parameters: (a) exterior air temperature and (b) exterior humidity level. Based on the exterior air temperature, the United States has been divided into eight *temperature zones*, ranging from zone 1 to zone 8. Zone 1 represents a location that is warm throughout the year (and hence cooling dominated), and zone 8 refers to a location that is subarctic (hence, heating dominated). Zones 2 through 7 fall within the two extremes represented by zones 1 and 8.

To account for exterior humidity, the United States has been divided into three *humidity divisions*: Division A (moist), Division B (dry), and Division C (marine).

Temperature zones and humidity divisions have been used by the U.S. Department of Energy (DOE) to develop a comprehensive *climate zone map* of the United States, Figure 5.28. The DOE's (hygrothermal) climate zone map is referenced by the building codes to prescribe the thermal properties of a building's envelope and other energy-efficiency requirements.



All of Alaska is in Zone 7 except the following boroughs in Zone 8: Bethel, Dellingham, Fairbanks N. Star, Nome, North Slope, Northwest Arctic, Southwest Fairbanks, Wade Hampton, and Yukon-Koyukuk.

Zone 1 also includes Hawaii, Guam, Puerto Rico, and the Virgin Islands.

FIGURE 5.28 Climate zone map of the United States.
Source: From VOLUME 7.1 High-Performance Home Technologies: Guide to Determining Climate Regions by County by Michael C. Baechler, Jennifer Williamson, Theresa Gilbride, Pam Cole, Marye Hefty, Pat M. Love., by U.S. Department of Energy.

EXPAND YOUR KNOWLEDGE

Climate Classification—The Climate Zones

The climate classification of the United States represented by the climate zone map of Figure 5.28 was developed specifically for prescribing energy-efficiency measures in buildings. This classification is not valid for other purposes, such as studying the relationship between climate and agriculture, climate and animal diversity/behavior, and so on. Other climate classifications exist for these purposes.

Only two climate parameters—*outside humidity* and *outside air temperature*—were considered important for the classification, disregarding other climate parameters such as solar radiation, precipitation, wind speed, and so on. As previously stated, according to this classification, a location lies within one of the eight temperature zones (zone 1 to zone 8), and within one of the three humidity regions (A, B, and C).

Humidity Regions: Of the three humidity regions, two regions—moist (region A) and dry (region B)—each cover approximately 50% of the continental United States. The division between the two regions is indicated by a virtual straight line that distinguishes the moist eastern half of the United States from the dry western half. A thin strip along the Pacific Coast has been designated as region C (marine) to recognize its mild summer climate, requiring little or no summer cooling in a typical building.

Temperature Zones: The eight temperature zones of climate classification are based on two fundamental indices related to the outside air temperature: *heating degree days* (HDD) and *cooling degree days* (CDD). Both HDD and CDD have numerical values for a location, which have been found to correlate fairly well with the annual energy consumption of a typical building. (A reader interested in learning more about HDD and CDD is referred to books that deal with these two indices.)

Climate Zones of the United States

With 8 temperature zones and 3 humidity regions, a total of (8 × 3 =) 24 climate zones are possible. However, in the United States only 15 zones exist. The reason for developing 24 zones is to make climate classification applicable globally (outside the boundaries of the United States) and to allow future modifications. (A revision of the climate zones in 2014 has introduced Zone Zero (0), referred to as *Extremely Hot*, which identifies some of the equatorial regions of Africa, Middle East, and South Asia.)

In the International Energy Conservation Code, the thermal properties required of building envelope components are based primarily on temperature zones (disregarding the humidity regions, except the Marine region). Both humidity regions and temperature zones are, however, needed for the specification of some aspects of the HVAC equipment.

5.15 THE INTERNATIONAL ENERGY CONSERVATION CODE

An important document regulating the design of buildings in the United States for energy conservation is the *International Energy Conservation Code* (IECC), published by the International Code Council. This document, which is updated every three years like the other ICC codes, deals with all aspects of energy use in buildings, that is:

- Building thermal envelope (shown in Figure 5.27)
- HVAC systems
- Service water heating
- Lighting systems (artificial lighting and daylighting)
- Electrical systems—transformers, horizontal and vertical transportation, on-site power generation, and so on

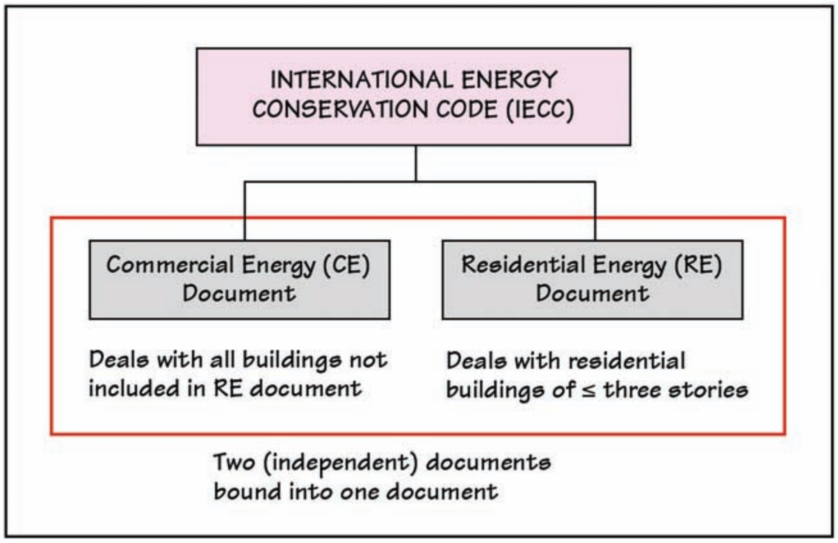

INTERNATIONAL ENERGY CONSERVATION CODE (IECC)
Commercial Energy (CE) Document
Residential Energy (RE) Document
Deals with all buildings not included in RE document
Deals with residential buildings of ≤ three stories
Two (independent) documents bound into one document

FIGURE 5.29 Formatting of the International Energy Conservation Code (IECC).

The IECC document is effectively a combination of the following two completely separate and independent documents, which are bound into one comprehensive document, Figure 5.29.

Residential Energy (RE) document of the IECC applies to residential occupancies such as one- and two-family dwellings, townhouses, and multifamily dwellings up to three stories high (see also Figure 2.14).

Commercial Energy (CE) document applies to all occupancies not included in the RE document. In other words, CE document includes provisions for commercial as well as residential buildings that do not form a part of the RE document. Hence, the energy efficiency of an apartment building of four or more stories is designed based on CE document, while that of three or fewer stories is designed based on the RE document. Similarly, energy conservation in a one- or two-family dwelling of ≥4 stories is regulated by the CE document.

While the code provisions are different in RE and CE documents, there are similarities in details related to their compliance. Because our focus is on the building thermal envelope, the following discussion relates to the envelope provisions.

COMPLIANCE WITH BUILDING THERMAL ENVELOPE PROVISIONS OF RE AND CE DOCUMENTS

Some provisions of IECC are mandatory, while the others allow alternative paths of compliance. Mandatory provisions deal with requirements that must be met in every building regardless of the compliance path chosen for nonmandatory provisions. For example, the provision dealing with air leakage through the thermal envelope is mandatory (air leakage is covered in Chapter 6). The nonmandatory provisions of thermal envelope can be complied with by following one of the three alternative compliance paths described here and graphically illustrated in Figure 5.30.

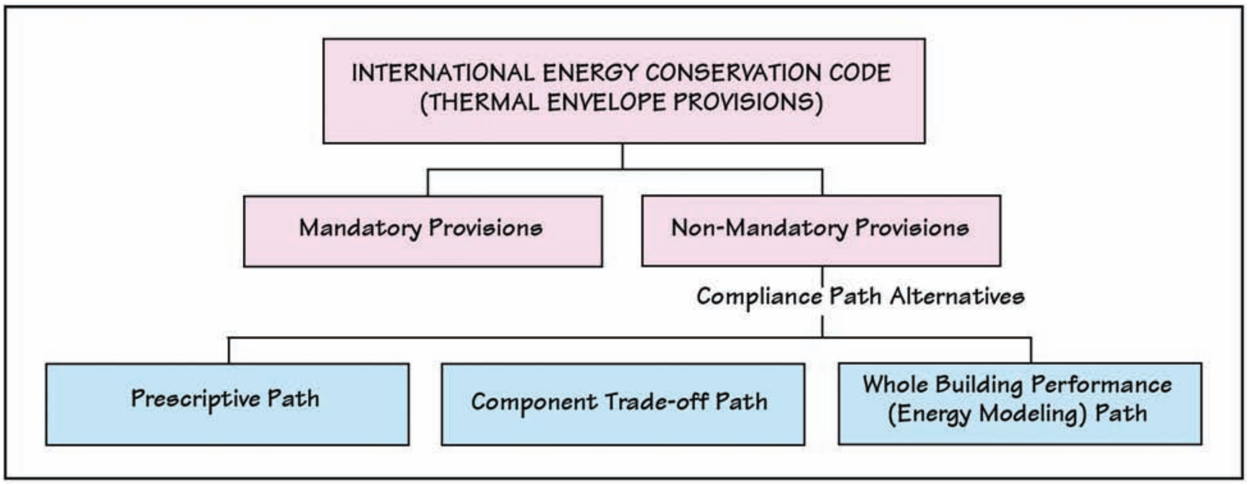

INTERNATIONAL ENERGY CONSERVATION CODE (THERMAL ENVELOPE PROVISIONS)
Mandatory Provisions
Non-Mandatory Provisions
Compliance Path Alternatives
Prescriptive Path
Component Trade-off Path
Whole Building Performance (Energy Modeling) Path

FIGURE 5.30 Compliance options in the International Energy Conservation Code (IECC).

1. **Prescriptive Path** requires complying with the minimum R-values given in IECC of various opaque assemblies of the thermal envelope (below-ground walls, opaque above-ground walls, opaque exterior doors, floors, and roof), prescriptive thermal properties of glazed fenestration (U-factor and SHGC; SHGC is described in Chapter 30), and prescriptive thermal properties related to roof coverings (solar reflectance and emissivity, discussed in Chapter 33). An important point to notice is that for the opaque assemblies, continuous insulation is mandated by IECC for most situations. This aspect is further highlighted in Section 5.16.

   As an alternative to minimum R-values for the opaque assemblies, IECC gives their maximum U-values. Using this alternative, the designer may decide not to use continuous insulation, but must establish that the U-values of the assemblies used meet the code requirement. In both prescriptive path alternatives, the total area of glazed fenestration is limited by the IECC.

2. **Component Trade-off Path** allows trade-off between the thermal efficiency of one component of the thermal envelope with another as long as the total heat transfer through the entire thermal envelope does not exceed that obtained by using the prescriptive path. In other words a larger amount of insulation in opaque walls can compensate for less thermally efficient windows. This path allows the limit on fenestration area to be ignored.

   The component trade-off path is obviously more complicated than the prescriptive path, but gives greater freedom in design. Simple-to-use, free-downloadable software developed by the U.S. Department of Energy (COMcheck for CE document and REScheck for RE document) are available for use by designers.

3. **Total Building Performance Path**, also called the **Energy Modeling Path** allows trade-offs between the energy consumed by the thermal envelope, and all mechanical and electrical systems used in the building. In other words, the IECC requires that the cost of the total annual energy consumed by the building (using this path) should not exceed that consumed by the same building using the *standard reference design* (SRD).

   Thus, the owner may decide to use a more efficient HVAC system, or lighting system and trade it off with a less efficient building envelope, or vice versa. The cost of energy for SRD is obtained by assuming that the proposed building meets all mandatory and prescriptive requirements of the envelope, as well as those of mechanical and electrical systems of the building. This path is far more complicated than the other two paths and is used only in larger buildings where the use of complex commercial software and the employment of energy consultants can be justified.

5.16 CONTINUOUS ENVELOPE INSULATION REQUIRED

As shown in Section 5.11, thermal bridging can substantially degrade the insulating property of the envelope. The IECC therefore places a great deal of importance on this fact by requiring that the insulation in the building thermal envelope be continuous. Continuous insulation (CI) is defined by IECC as the insulation that is continuous across members of the envelope assembly that provide structural support (such as wood or steel studs in a wall assembly), that is, the thermal envelope assembly must be without thermal bridges. An exception is permitted for fasteners and service openings.

CONTINUOUS INSULATION ON INSIDE OR OUTSIDE FACE OF ENVELOPE

Although the IECC does not specifically mention whether the continuous insulation be on the inside face, outside face or somewhere in the middle of the envelope thickness, its placement on the outside face is more effective because it moderates the temperature of the supporting members of the assembly and the structural components of the building, reducing their expansion and contraction, thereby increasing their life span.

Only when a building is intermittently heated or cooled, such as a church hall, the interior placement of a part of the insulation may be considered. The interior placement of insulation allows faster heating or cooling of interior air because it reduces energy loss to heat or cool the structural components of the building.

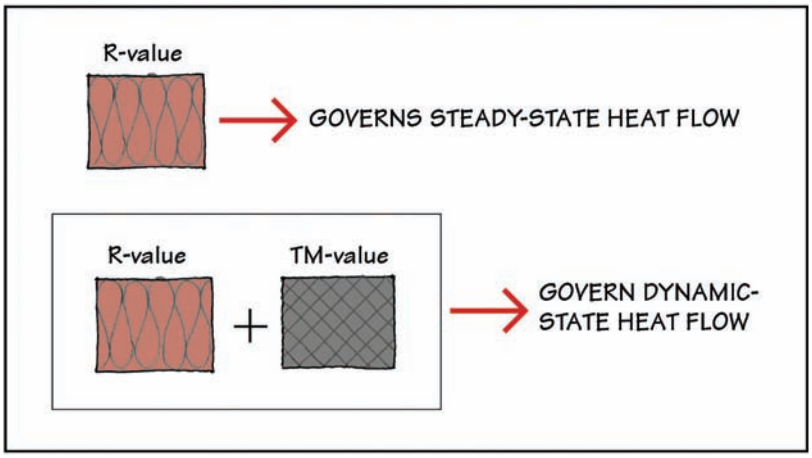

R-value
GOVERNS STEADY-STATE HEAT FLOW
R-value
TM-value
+
GOVERN DYNAMIC-STATE HEAT FLOW

FIGURE 5.31 Building thermal envelope properties that govern heat flow under steady and dynamic states.

5.17 THERMAL MASS

The concepts of heat flow and the related thermal properties of materials discussed in earlier sections apply to *steady-state* heat transfer. A steady state is defined as the state in which the temperatures at all points within an assembly remain constant over time. The opposite of steady state is unsteady state, more commonly referred to as a *dynamic state*.

With particular reference to the building thermal envelope, a steady state implies that the temperatures on both sides of the envelope are constant over time. In practice, a perfect steady state does not occur because although the inside air temperature may be kept constant by heating or cooling, the outside envelope temperature varies over time.

The outside temperature of the envelope is a function of the outside air temperature and the intensity of solar radiation. On days when the sun's rays are absent—that is, an overcast sky—the daily variation in the outside temperature is small. Thus, an approximation of a steady state is obtained when: (a) the indoor temperature of the building is kept constant and (b) the outdoor temperature registers little daily variation.

A dynamic state is more common than a steady state. In a dynamic state, the temperature at a point within a component varies with time due to the variation of outside air and surface temperatures. This occurs in climates where solar radiation intensities are high, resulting in large daily and seasonal variations in the outside air temperature.

The distinction between steady and dynamic states has an important bearing on a building envelope's thermal properties. The property of a building component that governs heat transfer under a steady state is its R-value. In other words, under a steady state, it is the insulation in the envelope that governs the heat flow. Under a dynamic state, both the R-value (insulation) and the envelope's ability to store heat come into play, Figure 5.31.

THERMAL MASS OF AN ELEMENT

The ability of a building element to store heat is referred to as its *thermal mass*, which is defined as the amount of heat needed to raise the temperature of 1 ft^2 of the element by 1°F. The greater the thermal mass of the element, the greater the amount of heat it will absorb for a given rise in its temperature. *Thermal capacity* and *thermal inertia* are other terms that are used synonymously with *thermal mass*.

Like the R-value, thermal mass (TM) is a property of the element. For building materials, TM is directly proportional to the surface density of the element, that is, proportional to weight per ft^2 (lb/ft^2) of the element. For the same thickness of the element, dense materials, such as concrete, brick, stone, and adobe, have a higher thermal mass than lightweight materials, such as the insulating materials. Wood is an exception to this rule of thumb because of the presence of water in it. Its thermal mass is higher than other building materials of the same thickness. Similarly, wet soil has higher thermal mass than dry soil.

THERMAL MASS (TM) VERSUS R-VALUE

Because both TM and R-value affect heat transfer through the envelope, what is the relative importance of the TM and R-value of the envelope? It has been shown that the amount of energy consumed in heating or cooling buildings is almost independent of the TM of the envelope, provided that the heat flow through the envelope remains unidirectional—that is, if heat flows either from the inside to the outside or from the outside to the inside.

Under unidirectional heat flow, only the R-value of the envelope (i.e., the insulation) determines the energy consumption of a building. The envelope's TM plays an insignificant role under unidirectional heat-flow conditions, even when unidirectional heat flow is dynamic. On the other hand, if heat-flow direction changes over time (from the outside to the inside at some times and from the inside to the outside at other times), both the R-value and the TM of the envelope

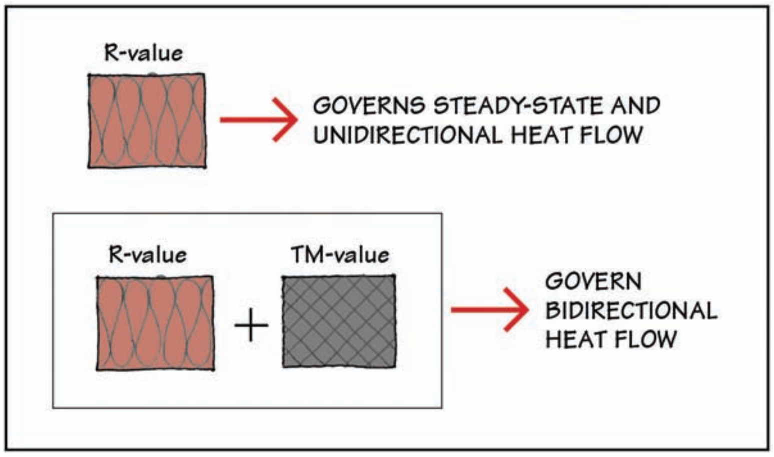

R-value
GOVERNS STEADY-STATE AND UNIDIRECTIONAL HEAT FLOW
R-value
TM-value
+
GOVERN BIDIRECTIONAL HEAT FLOW

FIGURE 5.32 Building thermal envelope properties that govern unidirectional and bidirectional heat flows.

determine energy consumption. The statement of Figure 5.31 can, therefore, be modified as shown in Figure 5.32.

An obvious example of unidirectional heat flow is a cold storage room, where the heat flow is from the outside to the inside. Thus, in cold storage buildings, the envelope's insulation determines energy consumption. In extremely cold climates, the heat flow remains unidirectional (heat flows from the inside to the outside) for most of the year. Here, also, the insulation of the envelope is significant. TM plays a relatively insignificant role in such climates.

In some climates, where the daily temperature swing is extreme (say, 90°F daytime maximum and 50°F nighttime minimum), the heat-flow direction changes in a 24-h period. TM plays a role in such climates. A high TM will stabilize indoor temperature within the comfort range, and insulation may not be required at all in a well-designed building.

IECC AND THERMAL MASS

IECC takes into account the beneficial role of TM by requiring lower R-values in opaque parts of walls with high TM, called the *mass walls*. For example, the minimum R-value required of mass walls in climate zones 1 and 2 (warm climates where solar radiation produces dynamic exterior thermal conditions during much of the year) is R-5.6, while that required for wood frame walls is R-20 [Ref. 5.4]. In climate zones 3 to 8, the difference between the minimum required R-values for mass walls and lightweight walls decreases progressively.

A *mass wall* is defined by the IECC as a wall with a minimum surface density of 35 lb/ft^2 (psf). Typical examples of mass walls are concrete masonry walls or concrete tilt-up walls, discussed in Chapters 25 and 26, respectively.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

29. The U-value and R-value of an assembly are related to each other by which relationship?
a. $U = R$ **b.** $U + R = 1$
c. $(U)(R) = 1.0$ **d.** $U^2 + R^2 = 1.0$
e. None of the above

30. A building assembly with a higher U-value is thermally more insulating than one with a lower U-value.
a. True **b.** False

31. The units of measurement of U-value and U-factor are the same.
a. True **b.** False

32. A wall assembly (total area = 100 ft^2) consists of 80 ft^2 of opaque wall with an R-value of R-20 and a 20 ft^2 of window whose R-value is R-2. The effective (overall) R-value of the entire wall assembly is approximately
a. R-15. **b.** R-11.
c. R-7. **d.** R-3.
e. none of the above.

33. Which of the following steel stud wall assemblies gives a higher overall R-value? In both assemblies, the total amount of insulation is R-15.
a. Assembly A has an exterior insulating sheathing of R-5 and within-stud insulation of R-10
b. Assembly B has an exterior insulating sheathing of R-3 and within-stud insulation of R-12

34. A concrete slab-on-ground does not require to be insulated in warm climates.
a. True **b.** False

35. In climates where a concrete slab-on-ground must be insulated, it should be insulated under its entire area.
a. True **b.** False

36. The F-factor relates to heat flow through
a. glazed wall.
b. above-ground opaque wall.
c. basement wall.
d. a concrete roof slab.
e. a concrete slab-on-ground.

37. The walls of a conditioned basement must be insulated over the entire depth of the wall.
a. True **b.** False

38. The U.S. Department of Energy's climate zones are based on
a. the exterior air temperature. **b.** the exterior humidity.
c. precipitation. **d.** (a) and (b).
e. (b) and (c).

39. The coastal region of the western United States lies in
a. climate zone 1(A). **b.** climate zone 2(A).
c. climate zone 3(A). **d.** climate zone 4(A).
e. none of the above.

40. In which of the following buildings will heat flow occur unidirectionally?
a. Continuously heated or cooled buildings
b. Intermittently heated buildings
c. Intermittently cooled buildings
d. All of the above
e. None of the above

41. The International Energy Conservation Code provides
a. two alternative paths of compliance.
b. three alternative paths of compliance.
c. four alternative paths of compliance.
d. five alternative paths of compliance.
e. none of the above.

42. Insulation is most effective if it is placed
a. on the outside face of the assembly.
b. on the inside face of the assembly.
c. in the center of the assembly.

43. For energy conservation, materials with high thermal mass are effective in climates in which the heat flow through the building envelope is
a. bidirectional within a 24-h period during a large part of the year.
b. unidirectional within a 24-h period during a large part of the year.
c. absent during a large part of the year.

44. A wall framed with wood or steel studs is a mass wall.
a. True **b.** False

PRINCIPLES IN PRACTICE

Commonly Used Insulating Materials

A large variety of insulating materials are currently used in buildings. They can be classified in several ways based on their configuration, physical structure, or combustibility. If classified on the basis of configuration, insulating materials are classified as either *rigid insulation* or *flexible insulation*. Rigid insulation is commonly used in flat roofs and may be in the form of rigid boards or poured-in-place lightweight concrete. Flexible insulation is commonly used in stud walls and attic spaces and may be in the form of blankets, batts, or loose-fill insulation. Graphically, we distinguish between the rigid and flexible insulations, as shown in Figure 5.33.

A classification that is more suitable for describing various insulations is based on the insulation's physical structure. According to this classification, insulating materials may be divided into the following three categories:

- Fibrous insulation
- Granular insulation
- Foamed insulation

Commonly used materials in each category are shown in Table 5.4.

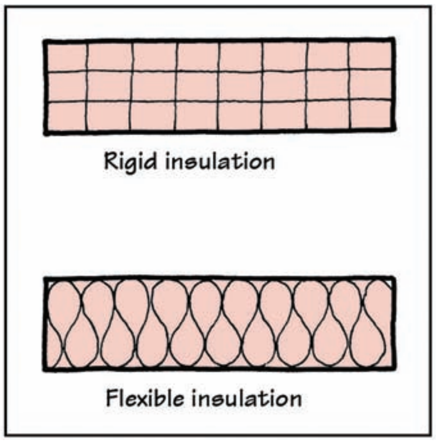


FIGURE 5.33 Graphical notations for rigid and flexible insulations for use in cross sections of building assemblies.

FIBROUS INSULATION

Fibrous insulating materials derive their high thermal resistivity from the air contained between the fibers. The fibers can be of mineral base or cellulosic base. Three types of mineral fibers are generally used: (a) glass fibers, called *fiberglass*, (b) fibers obtained from natural rock, called *rock wool*, and (c) fibers obtained from slag, called *slag wool*.

Fiberglass is made by fiberizing molten glass, and rock wool and slag wool are made by fiberizing molten rock and slag, respectively. The fibers are then sprayed with a binder and fabricated into the finished product. Fiberglass, rock wool, and slag wool insulations are fire resistant, moisture resistant, and vermin resistant.

Cellulosic fibers are derived from recycled newspaper, wood, and sugarcane. They are usually treated for fire resistance, minimization of smoke contribution, fungal growth, and decomposition by moisture.

Fiberglass is the most commonly used fibrous insulation and is available in the form of:

- Batts
- Blankets
- Semi-rigid boards

Batts and blankets are normally used as wall insulation. Semi-rigid boards are also used in walls, but in locations where greater rigidity is needed, such as in spandrel areas of glass curtain walls. Batts and blankets are similar in appearance, composition, and density. The only difference between them is that blankets are available in rolls, whereas batts are precut from rolls into standard dimensions.

Apart from other sizes, both batts and blankets are manufactured in standard widths to fit 12-in., 16-in., and 24-in. center-to-center spacing between wood or metal studs. They are available either unfaced, Figure 5.34, or faced, Figure 5.35. Facing usually consists of asphalt-impregnated paper, called *building paper*, which functions as a vapor retarder (see Section 6.7). Building

TABLE 5.4 COMMONLY USED INSULATING MATERIALS

Physical structure	Cofiguration	Insulating material
Fibrous insulation	Batts, blankets, and semi-rigid boards	Fiberglass Rockwool Slag wool
Granular insulation	Rigid boards	Perlite board Expanded polystyrene board (EPS)
Foamed insulation	Rigid boards	Extruded polystyrene board (XPS) Polyisocyanurate (ISO) board Cellular glass board
	Foamed-in-place	Polyurethane Icynene Foamed concrete

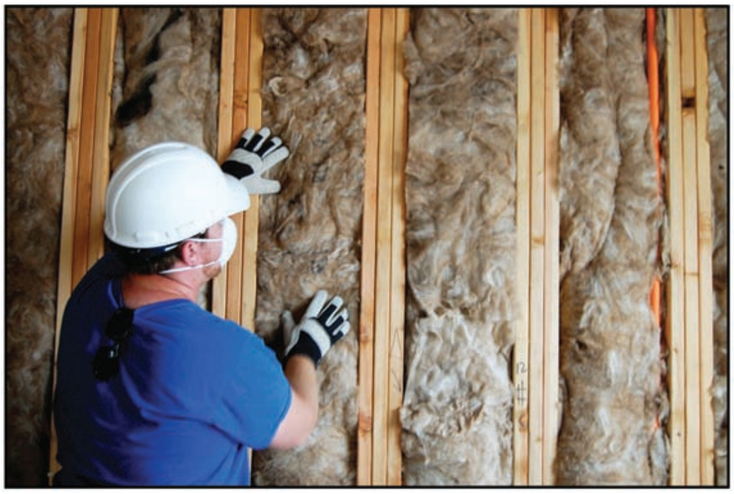


FIGURE 5.34 Unfaced fiberglass insulation being installed between studs. As shown in Figure 5.36, the insulation will be covered with a vapor retarder (where a vapor retarder is needed, see Section 6.8) before installing gypsum board on the studs.

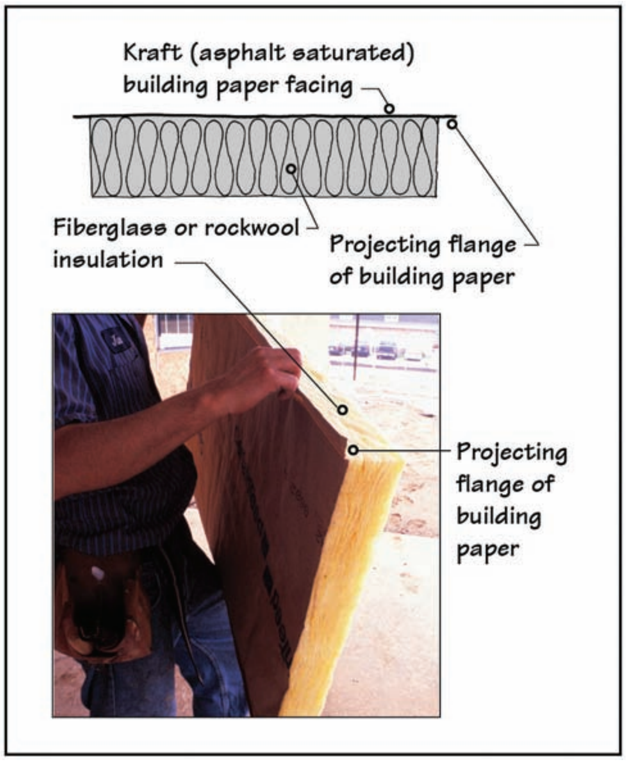

Kraft (asphalt saturated) building paper facing
Fiberglass or rockwool insulation
Projecting flange of building paper
Projecting flange of building paper

FIGURE 5.35 Projecting flanges of building paper–faced fibrous insulation.

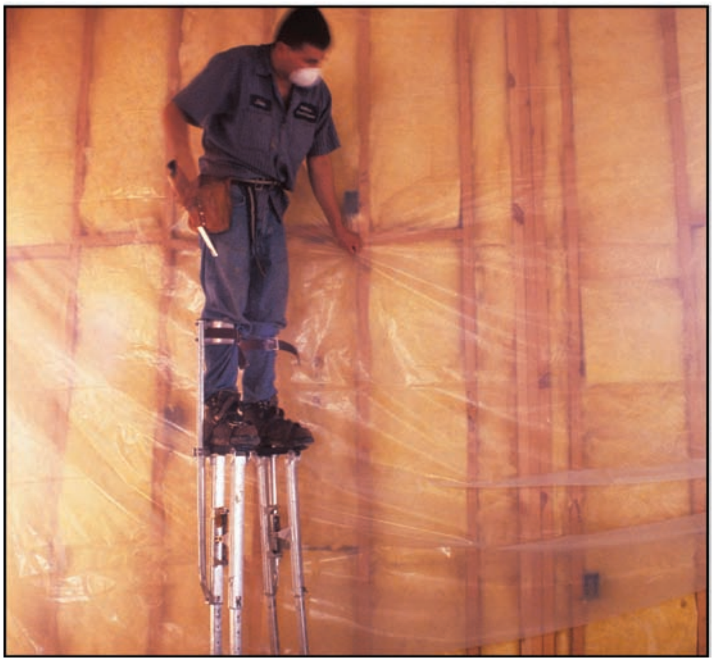


FIGURE 5.36 A clear polyethylene sheet vapor retarder being installed over unfaced fiberglass insulation between wood studs.

paper–faced insulations are generally available with projecting flanges for stapling to wood studs, as shown in Figure 5.35. Flanges may be stapled either to the faces of studs (face stapled) or to the sides of studs (inset stapled).

Unfaced batt insulation is used in climate zones where a vapor retarder is not required (see Section 6.8). Where a vapor retarder is required, it can be provided separately, Figure 5.36. Unfaced insulation is also used as an add-on insulation (retrofit) in ceiling spaces where some insulation and vapor retarder already exist.

Glass wool, mineral wool, or cellulosic fiber insulation may also be used as loose-fill insulation. These are usually blown into air spaces by pneumatic blowers. Blown-in insulation, Figure 5.37, is popular in retrofit applications (older buildings) where either no insulation or inadequate insulation existed previously. However, the potential for condensation within the insulation must be examined in a retrofit application, because the addition of insulation may create condensation where none existed earlier. Refer to Principles in Practice at the end of Chapter 6.

NOTE

Rock Wool and Slag Wool

Rock wool and slag wool are together referred to as *mineral wool*. Although both mineral wool and fiberglass are noncombustible, mineral wool is more fire resistant than fiberglass because it has a higher melting-point temperature. Slag is a waste product obtained from the manufacture of iron (see Chapter 18).

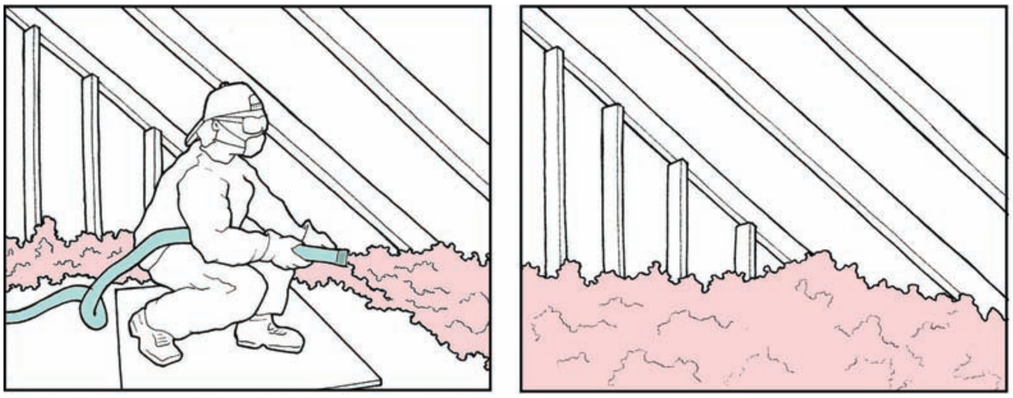


FIGURE 5.37 Blown-in fibrous insulation, commonly used in attic spaces for thermal insulation and in ceiling spaces of multifamily dwellings for sound insulation.

(Continued)

Commonly Used Insulating Materials (*Continued*)

GRANULAR INSULATION

In materials with a granular structure, the air voids are contained inside tiny hollow beads or granules. Two types of granules are in common use:

- Expanded perlite granules
- Expanded polystyrene (EPS) granules

Perlite is a glassy volcanic rock that is expanded into granules by heat treatment. The expansion of perlite takes place due to the 2% to 6% moisture present in the crude perlite rock. When heated suddenly to a temperature of nearly 1,600°F, the water in crushed perlite particles is converted to steam. The pressure of the steam expands the perlite particles, creating small air-filled granules, Figure 5.38. The process of expanding perlite is, in fact, similar to that of making popcorn.

Expanded polystyrene granules (also called *polystyrene beads*), popular as packing material, are used to make EPS insulation boards, as described in the following paragraph. Of the two granular materials, polystyrene granules are combustible, whereas perlite granules are noncombustible.

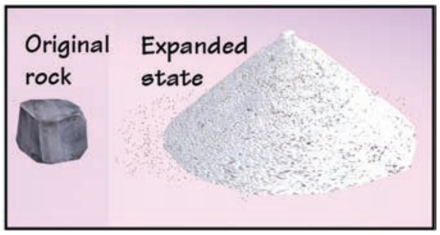


FIGURE 5.38 A piece of perlite rock which, when crushed and heated, expands substantially in volume. Although this illustration refers to perlite, it applies to all rocks that contain some water (see Figure 21.14).

PERLITE BOARD INSULATION

Both perlite and expanded polystryrene are used as rigid board insulation in buildings. Perlite boards are made with a combination of expanded perlite granules and mineral and cellulosic fibers. The fibers help increase the strength of the board. Asphalt is also added to the combination to improve water repellency and rot resistance. Perlite board is widely used as an insulation over (relatively flat) low-slope roof decks. It is noncombustible and can withstand the high temperature of hot asphalt.

EPS BOARD INSULATION

EPS boards—also referred to as *bead boards*—are made by packing polystyrene granules (beads), nearly $\frac{1}{8}$.in. diameter, in a mold and fusing them together under heat and pressure. The molded material is simply a large rectangular block, referred to as a *bun,* which is sliced into boards of required thickness, Figure 5.39. An EPS board is essentially of the same material as that used in picnic coolers.

Although the compressive strength of an EPS board is almost the same as that of a perlite board, it is not as widely used in low-slope (relatively flat) roof insulation because of its combustibility and its inability to withstand high temperatures. It is, however, commonly used in exterior insulation and finish systems (EIFS) wall systems (see Chapter 29).

EPS AND INSULATING CONCRETE FORMS (ICF)

An interesting use of EPS is in hollow blocks, which are used as formwork for concrete. Referred to as *insulating concrete forms* (ICF), ICF blocks are stacked and reinforced with steel bars, and their cells are filled with concrete to form an insulated, reinforced concrete wall, Figure 5.40.

When EPS is used as permanent concrete forms, ICF construction eliminates the use of conventional wood or steel formwork. ICF manufacturers have developed several innovative products, and ICF construction is being used as an alternative to traditional load-bearing wall construction in wood, masonry, and concrete.

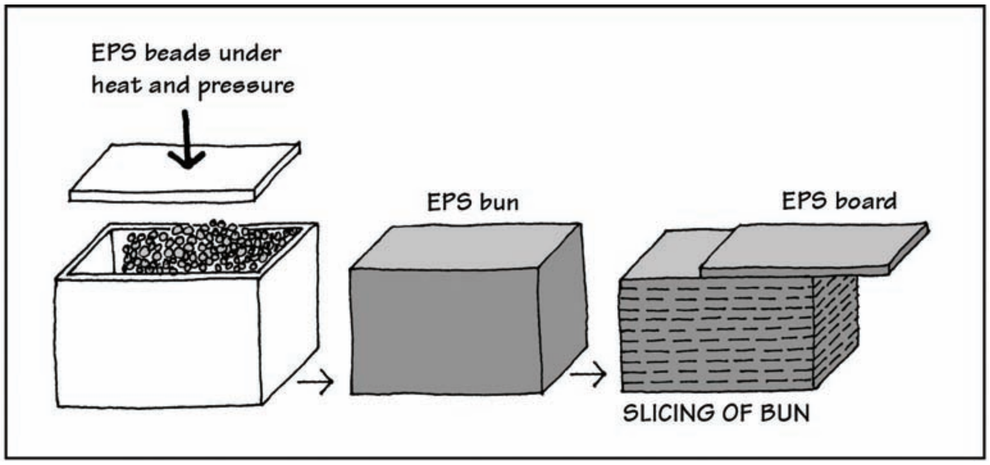
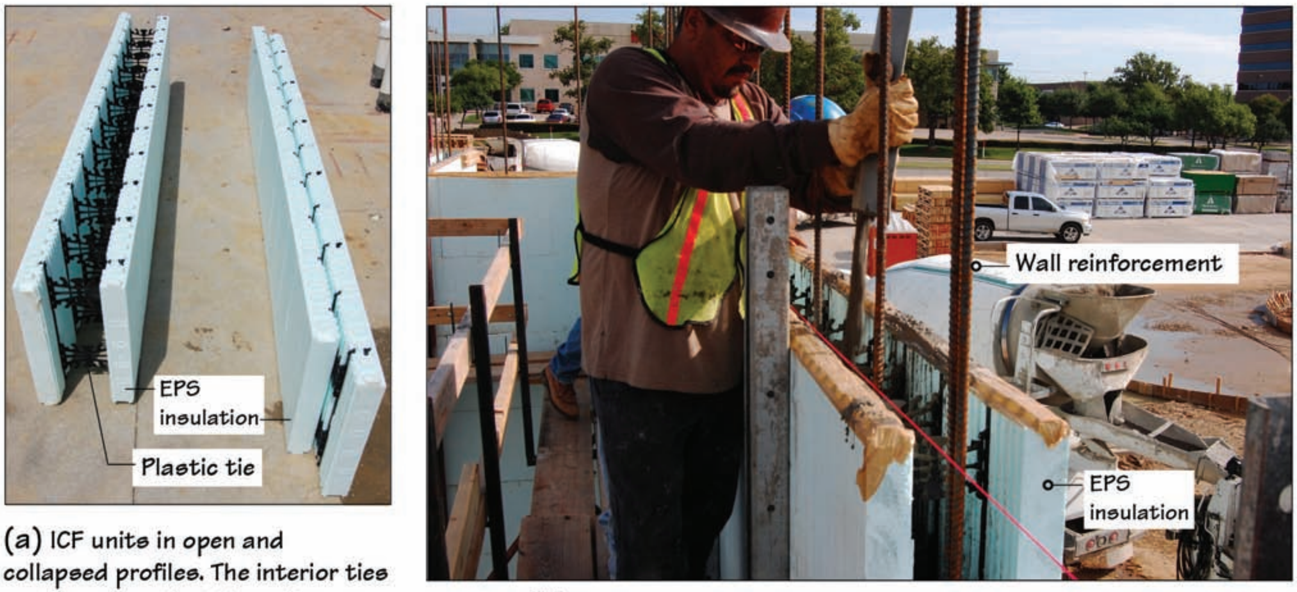


FIGURE 5.39 Manufacturing process of EPS boards.

PRINCIPLES IN PRACTICE



(a) ICF units in open and collapsed profiles. The interior ties are hinged so that the units can be collapsed for shipment. They are opened when laid in the wall.

(b) Concrete being placed in an ICF wall.

Fire retardant treated EPS panels with interior plastic ties constitute an ICF unit. The units are used as formwork for an insulated concrete wall, as shown in (b). Plastic ties, which connect the two opposite EPS panels of a unit, are permanently embedded in the wall's concrete.

FIGURE 5.40 Insulating concrete form (ICF) walls are used as exterior walls for residential and commercial buildings. The wall's high R-value makes ICF construction an attractive alternative where energy conservation is critical.

FOAMED INSULATION

The most commonly used insulating foams are synthetic (plastic) foams, such as *extruded polystyrene* and *polyisocyanurate*. Both are used as rigid boards, and their physical structure is cellular with closed cell cavities. The cavities contain HCFC gas.

The boards are made by the extrusion process. This process consists of forcing a semi-liquid material through an aperture (die). This is precisely the same concept as forcing toothpaste out of a tube, the mouth of the tube being the die. Polystyrene board obtained from the extrusion process is called *extruded polystyrene board* (XPS) to distinguish it from the molded EPS (beaded) board.

The extrusion process is complex and requires a large capital outlay in manufacturing. By contrast, the molding process is simpler and less expensive. That is why XPS boards are costlier than EPS boards but provide a higher ρ-value and higher compressive strength.

MAKING OF XPS BOARDS

XPS boards are made by mixing liquid polystyrene with liquid HCFC (as the blowing agent) and forcing the mixture through a die, Figure 5.41. XPS was first manufactured by the Dow Chemical Company in the United States during the 1940s under the trade name Styrofoam. However, today, several manufacturers make XPS boards and distinguish their products from each other by using different colors.

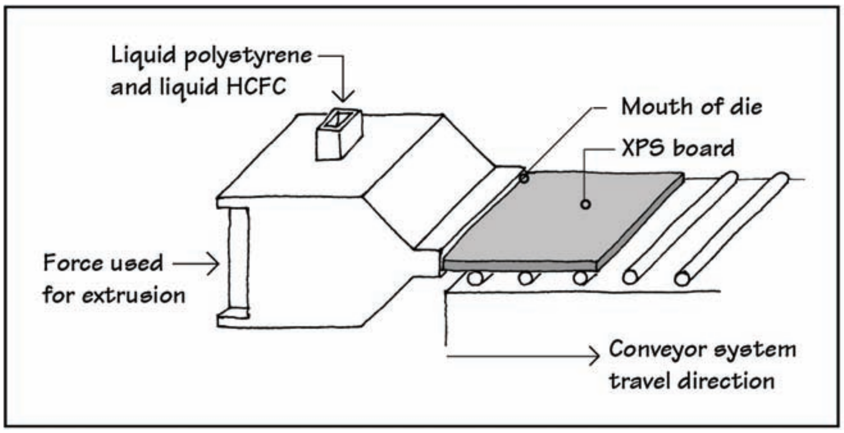


FIGURE 5.41 Manufacturing process of XPS boards.

(Continued)

Commonly Used Insulating Materials (*Continued*)

MAKING OF ISO BOARDS

The form of HCFC gas used as a blowing agent in the production of polyisocyanurate boards (commonly referred to as *ISO boards*) vaporizes at room temperature, so the liquid mixture of polymer and blowing agent is spread between the top and bottom facers to give ISO boards their required shapes. ISO boards are, therefore, manufactured with facers on both sides. XPS boards, on the other hand, do not require facers. The process of manufacturing ISO boards is shown in Figure 5.42.

The facers used on ISO boards retard the migration of HCFC gas out of the foam. Therefore, ISO boards have higher thermal resistivity than XPS boards. Facers consist of aluminum foil, glass fiber–reinforced polyester, plaster boards, wood fiber boards, and so on.

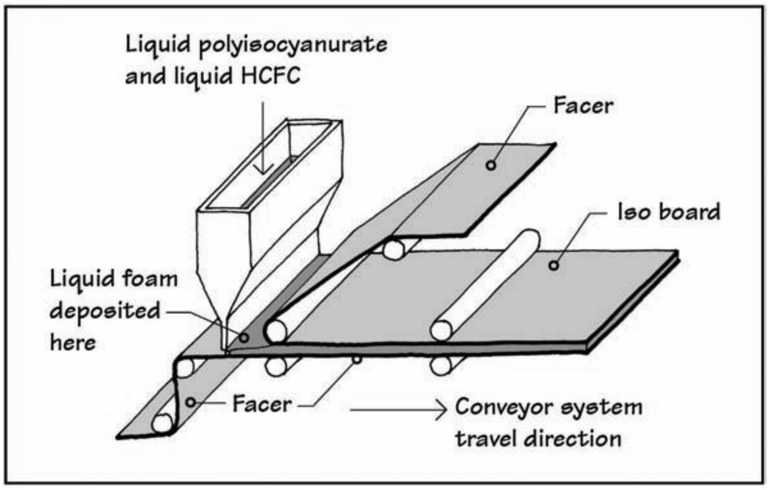

Liquid polyisocyanurate and liquid HCFC
Facer
Iso board
Liquid foam deposited here
Facer
Conveyor system travel direction

FIGURE 5.42 Manufacturing process of ISO boards.

USES AND LIMITATIONS OF XPS AND ISO BOARDS

The closed cellular structure of XPS and ISO boards implies that they have high resistance to water and water vapor penetration. An EPS board, being a beaded product, is relatively more permeable to water and water vapor than an XPS or ISO board (see Figure 5.6). Of the two boards, XPS and ISO, XPS board is the insulation of choice for below-grade insulation (slabs-on-ground, basement slabs, and walls) because it does not have any facers. Facers tend to degrade in subsoil conditions, particularly if they are of organic materials.

Both XPS and ISO boards are combustible and require protection from flames and high temperatures. They should not be used toward the interior of a wall. Building codes mandate that if used as interior insulation, they must be covered with a minimum of $\frac{1}{2}$-in.-thick gypsum board or an equivalent thermal barrier. They are resistant to fungal growth and chemical decomposition but can be destroyed when used below ground in heavily termite-infested soils. Polystyrene is sensitive to daylight and will deteriorate after prolonged exposure.

XPS and ISO boards are commonly used as insulation on flat or low-slope roof decks. ISO board is relatively more common as roof insulation because it can better withstand the high temperature of hot asphalt than XPS and is also more fire resistant. Other uses of XPS and ISO boards are in wall sheathing, basement walls, and insulation under slabs-on-grade.

FOAMED (CELLULAR) GLASS BOARDS

Another rigid-board foam product is foamed glass, also called *cellular glass*, which is made by expanding molten glass into a closed-cell structure and cooling it to form boards. Cellular glass boards have a much higher compressive strength than XPS or ISO boards. They are also impermeable to water vapor and water and are suitable as insulation in roofs that carry heavy loads, such as roof plazas and rooftop parking areas, as perimeter insulation under concrete slabs-on-grade under heavy loads, and below-grade insulation in termite-infested areas.

FOAMED-IN-PLACE INSULATION

Foamed-in-place insulation is formed by spraying a liquid chemical (or a mixture of two liquid chemicals) in position. The liquid foams, when sprayed, expand to nearly 30 times the original volume of the liquid. After expansion, the foam solidifies into a closed-cell structure in a few minutes. The advantage of foamed-in-place insulation is that it can be provided in preexisting cavities of odd shapes where other types of insulation would be less desirable or impossible to use.

A commonly used foamed-in-place insulation, called *polyicynene* by its manufacturer, is used for insulating stud cavities, Figure 5.43. The foam expands trapping air in its voids and solidifies in a few minutes, when it is shaved off to level with the studs. Its manufacturers claim that it fills the voids, providing a good air barrier.

FOAMED CONCRETE

Foamed concrete (also called *cellular concrete*) is a nonaggregate concrete that consists of Portland cement, water, and a liquid foaming concentrate. The foaming concentrate creates tiny air bubbles, so that when the mix hardens, it contains a matrix of air voids separated by pure Portland cement walls.

Foamed concrete is well suited for insulation on a flat (low-slope) roof because roof slopes can be easily created with wet concrete. The other method of providing slope on such a roof is to use tapered board insulation, which is far more

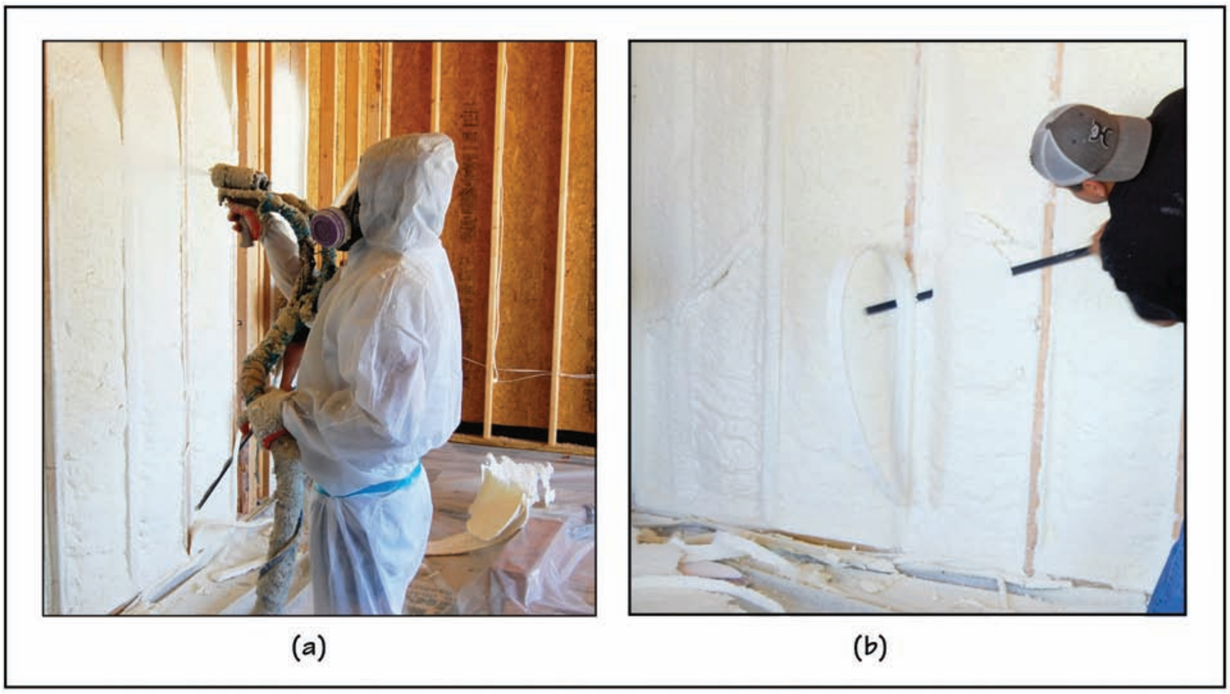


FIGURE 5.43 **(a)** Spraying of polyicynene insulation in stud cavities. **(b)** The insulation expands and cures (hardens) quickly, when it is shaved flush with the studs.

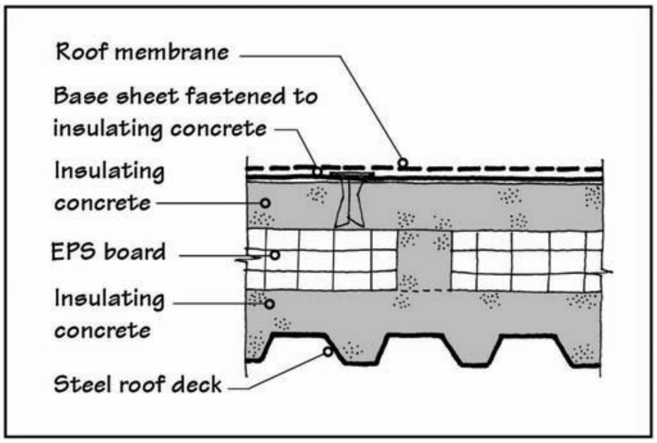

Roof membrane
Base sheet fastened to insulating concrete
Insulating concrete
EPS board
Insulating concrete
Steel roof deck

FIGURE 5.44 Cross section through an insulating concrete roof deck with sandwiched EPS boards.

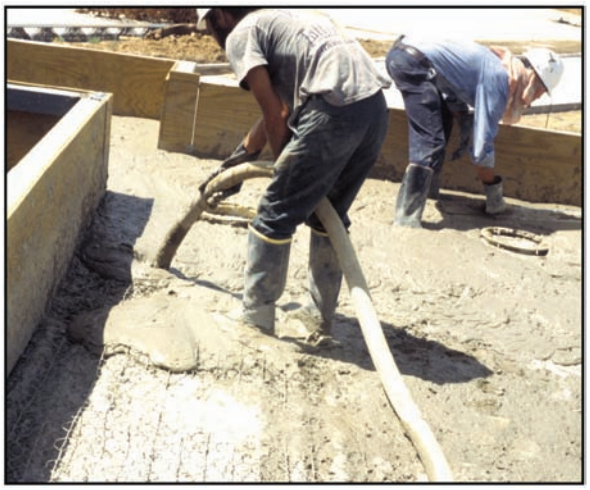


FIGURE 5.45 Insulating concrete being placed over roof deck.

labor intensive. Because foamed concrete bonds well to most roof substrates, such as reinforced concrete slab or steel deck, it provides high-wind-uplift resistance. It is also noncombustible.

The R-value of foamed concrete is lower than other roof insulations, for example, XPS and ISO boards. However, the advantages of foamed concrete, such as its fire resistance, easy sloping to drains, and good bonding to substrate, can be combined with the higher R-value of EPS boards to create a hybrid assembly. In this assembly, foamed concrete is poured below and above the EPS boards so that the EPS boards are sandwiched between the two layers of concrete, Figures 5.44 and 5.45. To structurally integrate the two layers of concrete and the EPS boards into a monolithic whole, the EPS boards are provided with holes, Figure 5.46.

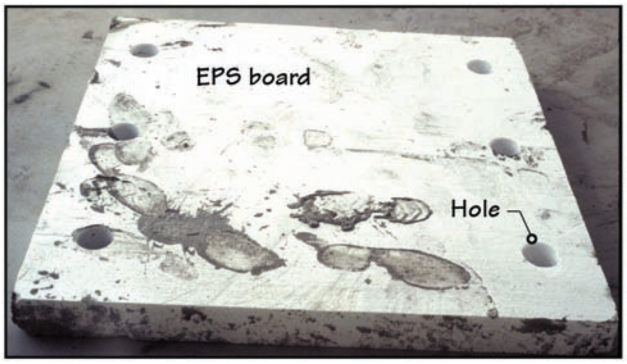

EPS board
Hole

FIGURE 5.46 Because EPS boards are sandwiched between two layers of concrete, the holes in EPS boards structurally integrate the layers.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

45. Which of the following plastic foam insulation contains air within its voids?
- **a.** Extruded polystyrene (XPS) board
- **b.** Expanded polystyrene (EPS) board (bead board)
- **c.** Polyisocyanurate board (ISO board)

46. Which of the following insulating materials is available in the form of rigid boards?
- **a.** Fiberglass
- **b.** Rock wool
- **c.** Insulating concrete
- **d.** Extruded polystyrene
- **e.** None of the above

47. Which of the following insulating materials is available in the form of batts?
- **a.** Fiberglass
- **b.** Expanded perlite
- **c.** Insulating concrete
- **d.** Extruded polystyrene
- **e.** None of the above

48. Which of the following insulations is combustible?
- **a.** Fiberglass
- **b.** Foamed concrete
- **c.** Perlite board
- **d.** Extruded polystyrene (XPS) board
- **e.** Vermiculite

49. In which of the following locations is blown-in insulation most commonly used?
- **a.** Stud wall cavities
- **b.** Masonry wall cavities
- **c.** Top of a flat roof
- **d.** Attic spaces

50. Foamed concrete is generally used as insulation in
- **a.** walls.
- **b.** steep roofs.
- **c.** foundations.
- **d.** all of the above.
- **e.** none of the above.

PRINCIPLES IN PRACTICE

Advanced Insulating Materials

AEROGEL INSULATION

Aerogel is the lightest solid material available with approximately 95% air by volume. The air in aerogel is contained in voids formed by a network of interconnected particles whose average diameter is 20 to 50 nm. ((1 nm $=$ 1 nanometer $= 10^{-9}$ m, or approximately 1/10,000 th of the thickness of human hair). Because of its nano-porous structure, aerogel has the highest R-value of any solid material so far known to humankind.

With R-10 for 1-in. thickness, aerogel is 150% better than the next best insulator—the ISO board—and 250% better than the most commonly used insulation—fiberglass. Additionally, aerogel's insulating property comes entirely from air spaces, unlike that of ISO board whose voids contain HCFC gas. The HCFC gas is detrimental to the environment (see Table 5.2).

The nano-size aerogel particles can be of several materials, such as silica (silicon dioxide, SiO2) and alumina (aluminum oxide, Al_2O_3). For insulation, silica aerogel is most commonly used. Because silica is essentially sand, aerogel is noncombustible unlike the ISO board, which, being a polymer, is combustible.

Aerogel was first used as an insulator in space shuttles for exploring the outer space. The fueling of space shuttles requires a large quantity of liquid oxygen and liquid hydrogen. For these gases to stay liquid, they must be held at temperatures of approximately −200°C, requiring an extremely high R-value material to insulate the chambers containing the liquids. Aerogel was the only material that suited this application.

Aerogel insulation is available in flexible, high-strength blankets and strips, typically $\frac{3}{8}$ in. thick. It is also available in bulk, as granules with mean particle diameter of approximately 0.5 mm. Being expensive, all three types are limited in use to situations where conventional insulation cannot be used.

Aerogel blankets are used to insulate undersea oil and gas pipes. These pipes comprise an assembly of two concentric pipes in which the inner pipe carries oil or gas and the insulation is contained in the space between the pipes. The use of conventional insulation would increase the diameter of the outer pipe so much that using aerogel is more economical.

Aerogel Insulation in Buildings

The use of 2 in.-wide, $\frac{3}{8}$-in.-thick aerogel strips has been promoted by one manufacturer to cover cold-formed steel studs in order to reduce thermal bridging, Figure 5.47. The insulating value of $\frac{3}{8}$-in.-thick aerogel insulation is R-4. However, the increase in the total R-value of the assembly with aerogel strips is only 1.75 [Ref. 5. 5]. In other words, simply covering the flanges of studs does not sufficiently reduce thermal bridging.

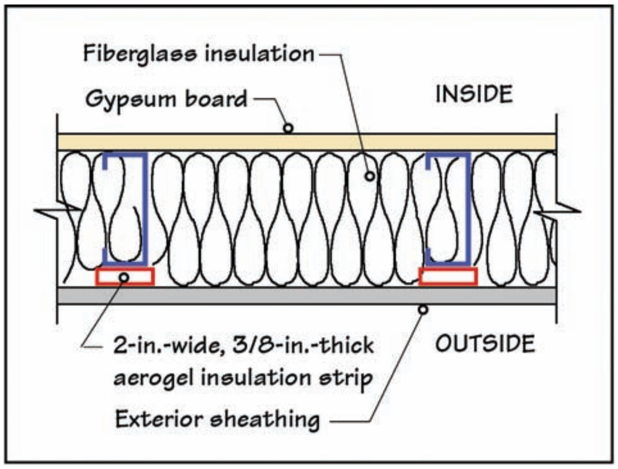


FIGURE 5.47 An exterior wall assembly framed with cold-formed steel studs whose flanges are covered with strips of aerogel insulation. This detail does not show other components of the assembly such as exterior wall finish, air-weather barrier, and so on.

PRINCIPLES IN PRACTICE

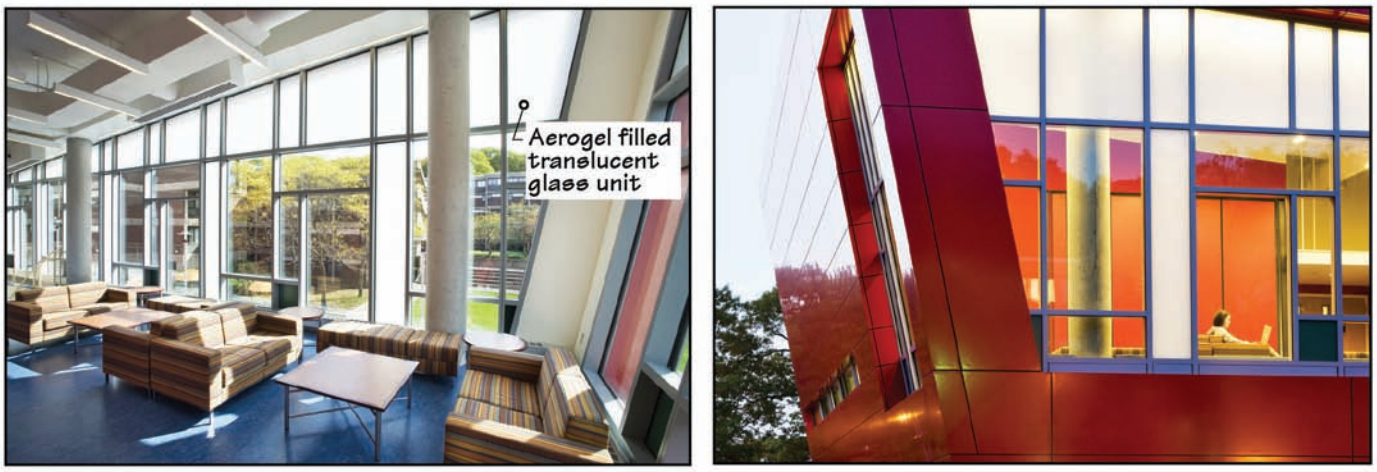


FIGURE 5.48 Silica aerogel-filled translucent glass units in Nobel Halls, State University of New York, (SUNY), Stony Brook, NY, LEED Silver rated building, completed Fall 2010. (Photos by Advanced Glazings.)

The most successful application of aerogel in buildings is in the form of granular insulation to fill the cavities of insulating glass units (IGU), used in windows and skylights. Because aerogel granules are translucent, aerogel-filled IGU provides (diffuse) light as well as insulation. A typical 1-in.-thick IGU with aerogel-filled cavity is rated at R-5. (Refer to Chapter 30 for the explanation of IGU.)

Figure 5.48 shows the use of aerogel insulated glazing in a LEED rated building. The aerogel-filled units are used in upper-level glazing, which are more effective in providing daylight as compared with lower-level glazing. The use of aerogel in skylights is far more promising than windows.

VACUUM INSULATION

Vacuum insulation in buildings borrows the concept from thermos flask, which essentially consists of two bottles, one inside the other with the space between the bottles (interstitial space) evacuated of air and sealed. Because of vacuum, convection and conduction are completely absent from the interstitial space. To reduce radiation heat transfer through this space, its surfaces are treated with low-emissivity material. Consequently, heat transfer through a flask is extremely small.

Vacuum insulation being considered for buildings consists of two types: (a) vacuum insulated panels (VIP) and (b) vacuum insulated glazing (VIG). VIP consist of a rigid structural core consisting of a material whose solid content is extremely small, such as aerogel or silica fume. Silica fume, which is a waste product from silicon industry (see Chapter 21), is less expensive, and hence more commonly used.

The silica fume core is wrapped with a high-strength, multilayered sheet and sealed. The air from this combination is evacuated, providing near-perfect vacuum. The entire assembly is then covered with a high-strength aluminized barrier, Figure 5.49.

The insulating value of 1-in.-thick VIP at the panel's center is approximately R-35, the overall value being approximately R-25. Manufacturers of VIP are targeting VIP for use within insulating glass units for spandrel areas of glass curtain walls.

VIG consists of two glass sheets with edges fused together, and the space between the two sheets (less than 1mm wide) comprises the vacuum. Regularly spaced tiny glass blobs, fused to both sheets integrate them structurally.

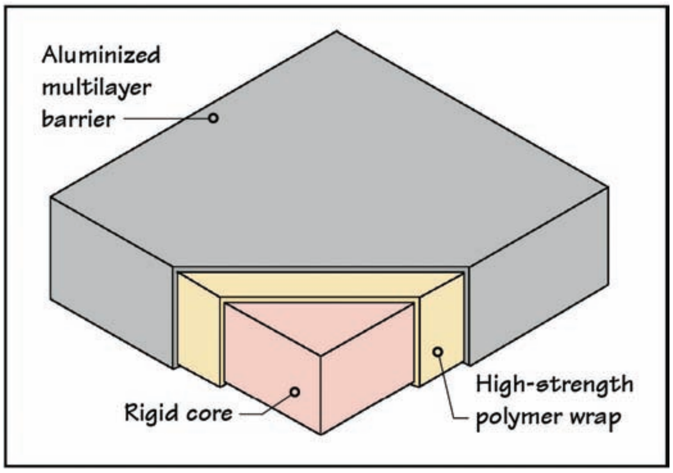


FIGURE 5.49 Anatomy of a vacuum insulated panel (VIP).

REVIEW QUESTIONS

1. Using the appropriate table, determine the individual R-values of the following materials:
   a. 4-in. nominal (actual $3\frac{5}{8}$-in.) thick brick wall
   b. $\frac{5}{8}$-in.-thick gypsum board
   c. 2-in.-thick extruded polystyrene (XPS) board
2. Draw a plan of the following wall assembly and then determine its total R-value, R_t. Starting from the outside face of the wall, the assembly consists of the following layers:

   4-in. nominal ($3\frac{5}{8}$-in. actual) brick veneer

   2-in. air space (cavity)

   0.75-in.-thick extruded polystyrene sheathing

   2 × 6 studs with $5\frac{1}{2}$-in.-thick fiberglass insulation

   $\frac{1}{2}$-in.-thick gypsum wallboard
   (Note: In calculating the value of R_t, ignore the presence of wood studs and assume that the entire layer consists of fiberglass insulation.)
3. What is the U-value of the assembly in Question 2? Does this value represent air-to-air heat transfer through the assembly? Explain.
4. What is aged R-value? To which materials does this concept apply and why?
5. Determine the U-factor of the following roof assembly. The opaque part of the assembly, with an area of 2,500 ft^2, has an overall R-value of 35. There is a skylight in the roof, which has an area of 100 ft^2, and its overall R-value is 2.0.
6. Using sketches and notes, explain the difference between:
   a. U-value and U-factor
   b. U-factor and C-factor
7. Determine the U-factor of the wall assembly in Question 2, which consists of 15% glazed area, and the U-value of glazing is 0.65.
8. Using sketches and notes, explain why it is unnecessary to insulate under an entire concrete slab-on-ground.
9. Explain the advantages of continuous insulation in envelope assemblies and why it is better to have the continuous insulation on the exterior face of the envelope. Where is inside placement of continuous insulation in the envelope desirable?
10. What are high-thermal-capacity materials? What is the definition of mass walls per the International Energy Conservation Code? In which climates are high-thermal-capacity materials effective?

CHAPTER 6

Properties of the Envelope–II (Air and Water Vapor Control)

CHAPTER OUTLINE

6.1 LEAKAGE AND DIFFUSION

6.2 AIR LEAKAGE CONTROL

6.3 AIR DIFFUSION CONTROL

6.4 WATER VAPOR IN AIR

6.5 CONDENSATION OF WATER VAPOR

6.6 VAPOR DIFFUSION AND CONTROL OF CONDENSATION

6.7 MATERIALS USED AS VAPOR RETARDERS

6.8 VAPOR RETARDERS AND CLIMATE ZONES

6.9 IMPORTANCE OF ATTIC VENTILATION

PRINCIPLES IN PRACTICE: CONDENSATION ANALYSIS—WHERE DEW POINT OCCURS IN AN ASSEMBLY

Thermal insulation, discussed in Chapter 5, controls only the flow of energy through a building envelope, and energy flow is only one of the several environmental factors that must be controlled in the design of a building envelope. The other important environmental factors, intimately related to energy, are: (a) air, (b) water vapor, and (c) liquid water. In this chapter, we will focus on air and water vapor control. Issues related to water infiltration control are covered in Chapter 27, immediately preceding the chapters (Chapters 28 and 29) that deal with the construction of exterior wall cladding.

AIR

Outside air often contains dust, pollen, ozone, and other pollutants. Inside air is typically subjected to mechanical conditioning (heated/cooled, humidified/dehumidified, and filtered). The unregulated flow of outside air to the interior not only introduces pollutants but also increases energy consumption because the outside air entering the envelope uncontrolled is not subjected to such conditioning.

The entry and exit of such air (called air *infiltration* and *exfiltration*, respectively) take place through cracks, gaps, voids, unsealed joints, and at the interface between envelope assemblies. It is important to note that the amount of air infiltration must equal exfiltration. This fact ensures that the interior spaces are neither pressurized nor depressurized. Therefore, collectively, we refer to air infiltration and exfiltration as *air leakage*. Air leakage is essentially unwanted ventilation, which must be reduced to the extent possible.

WATER VAPOR

Water and water vapor (collectively called *moisture*) are essentially the same material but in different states—water is a liquid, and water vapor is a gas. Water vapor generally occurs in combination with air. The leakage of air through the envelope is, therefore, always accompanied by the leakage of water vapor.

The movement of water vapor through the envelope assembly can cause significant problems if it converts to (liquid) water through condensation. Water wets the insulation and reduces its R-value, corrodes metals, promotes insect infestation, creates dampness giving rise to mold and fungi, peels off paints, and reduces the strength of cellulose- and gypsum-based materials. Controlling water vapor flow (in order to prevent its condensation within the envelope) is, therefore, essential.

6.1 LEAKAGE AND DIFFUSION

Before proceeding, it is important to understand that leakage is one of the two means by which a gas can migrate into and out of its container. The term *leakage* has already been defined as the migration of a gas (such as air and water vapor) through gaps, cracks, and voids in a container (building envelope). The migration of air and water vapor can also occur even when the envelope is fully sealed (without any gaps and voids, so that there is no leakage). Such migration is called *diffusion*. Although diffusion and leakage lead to the same end result, their mechanisms are different. Diffusion refers to the movement of a gas through the body of the container (envelope), whereas leakage refers to its movement through (unintended) holes in the envelope—for example, at joints between components.

Consider a rubber or latex balloon inflated with air or some other gas, Figure 6.1. Sooner or later, the air (or gas) will migrate out of the balloon. If the balloon wall is thicker, it may take a few days longer for the balloon to deflate than if it is thinner, but deflation will eventually occur. It will happen even if the mouth of the balloon (the only leakage site) is fully sealed. Obviously, the migration of air or gas in this situation occurs through the body of the balloon, not through any hole. This migration is diffuse migration or simply diffusion.

What has been shown in Figure 6.1 to occur with respect to a balloon also occurs in building assemblies, as shown for a concrete masonry wall, Figure 6.2. Here, the air and water vapor diffuse through concrete masonry units. Leakage takes place through joints between individual masonry units, the joints between the units and the supporting structure (such as the beam), and the joints between the units and any other component that abuts the units.

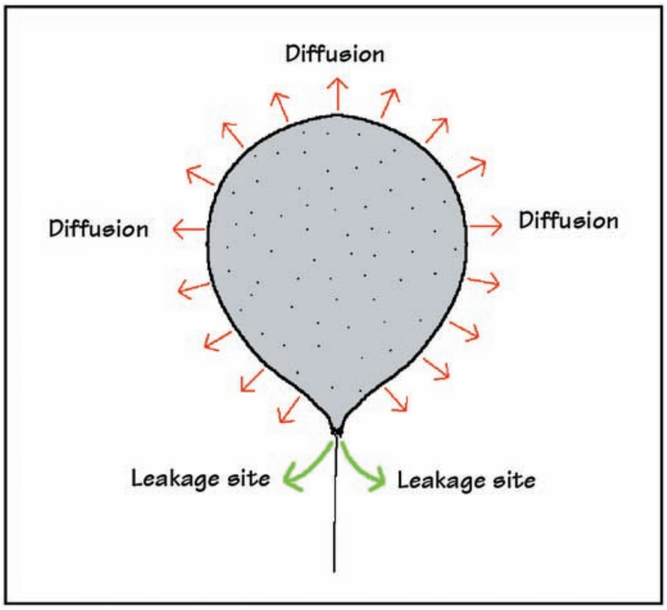


FIGURE 6.1 Difference between leakage and diffusion of a gas through a balloon.

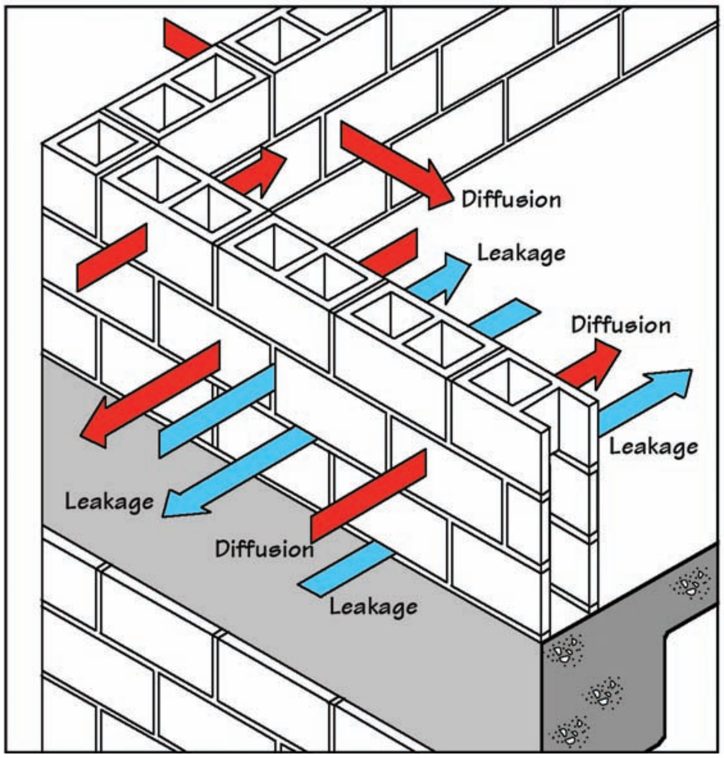


FIGURE 6.2 Difference between leakage and diffusion, shown for a concrete masonry wall.

RATE OF DIFFUSION—THE PERMEABILITY OF A COMPONENT

The rate of diffusion of a gas (in our case, air or water vapor) through a component is called its permeability. Permeability of a component is a function of: (a) the component's material, (b) component's thickness, and (c) the pressure difference (air pressure or vapor pressure difference) across the component. The permeability of a given component increases with increasing pressure difference across it, but decreases with its increasing thickness. Thus, a $\frac{1}{4}$-in.-thick plywood panel is more permeable to air or water vapor than a $\frac{1}{2}$-in.-thick plywood panel under the same pressure difference, Figure 6.3. Therefore, to compare the permeability of two components, we must test them under the same pressure difference. As we will see later in this chapter, building materials and components have different permeability values for air and vapor, and some materials, such as glass and metals, are impermeable to both air and vapor.

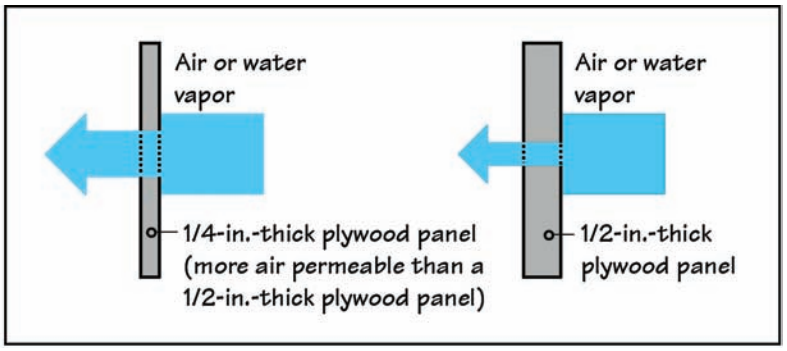

Air or water vapor
1/4-in.-thick plywood panel (more air permeable than a 1/2-in.-thick plywood panel)
Air or water vapor
1/2-in.-thick plywood panel

FIGURE 6.3 The permeability of a gas by diffusion, such as air or water vapor, increases if the thickness of the material is reduced, as shown here for two plywood panels, one $\frac{1}{2}$-in.-thick and the other $\frac{1}{4}$-in.-thick.

DIFFUSION CONTROL

To reduce the migration of air or vapor through the envelope, both leakage and diffusion must be controlled. Sealing the cracks, holes, and gaps reduces leakage but not diffusion. Diffusion reduction requires additional strategies as explained in Sections 6.3 and 6.6. In most contemporary buildings, however, leakage accounts for most air and vapor migration through the envelope. Sealing the envelope is, therefore, fundamental to controlling the passage of air and vapor.

6.2 AIR LEAKAGE CONTROL

Two factors affect air leakage in a building:

- Leakage area
- Pressure difference between inside and outside air caused by: (a) wind and (b) temperature

LEAKAGE AREA

The leakage area is a measure of the relative tightness of the envelope. It is the area of cracks, tears, holes, and openings in the envelope and is a function of the type of construction, design, and workmanship. The leakage sites in the envelope usually occur at the joints between various components, such as exterior doors, windows, skylights, fireplaces, electrical outlets, plumbing, and duct penetrations.

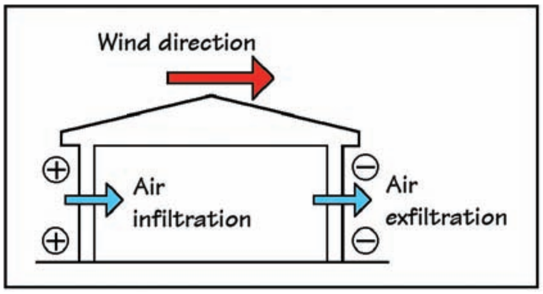


FIGURE 6.4 Air leakage (infiltration and exfiltration) through a building due to the pressure difference created by wind. Because wind creates positive (+) pressure on windward face of a building and suction, that is, negative (−) pressure on other faces, air leakage occurs through the building as shown.

AIR PRESSURE DIFFERENCE DUE TO WIND

We observed in Section 3.4 that the windward face of a building is under positive pressure and the other faces are under suction (negative pressure). Therefore, air infiltrates through the windward face and exfiltrates through the nonwindward faces of the building, Figure 6.4. This process is accelerated with increasing wind speed.

AIR PRESSURE DIFFERENCE DUE TO TEMPERATURE

Another factor that affects the inside-outside air pressure difference is the difference between the inside and the outside air temperatures. Because the density of air increases with decreasing temperature, cool (more-dense) air exerts higher pressure than warm (less-dense) air. Thus, during the cooling season, cool inside air has higher pressure than warm outside air. This leads to continuous exfiltration of cool air and infiltration of warm outside air through the envelope, Figure 6.5(a). During the heating season, the process is reversed, Figure 6.5(b).

Because the inside-outside pressure difference is primarily a function of the outside climate (wind speed and air temperature), there is little that can be done to control it. Thus, the only means of reducing air leakage in a building is to reduce the leakage area in the building envelope. This requires sealing all joints between building components (joints between exterior sheathing panels, between door/window frame and wall, between door frame and door, etc.). Sealants between fixed components are typically nonhardening synthetic compounds

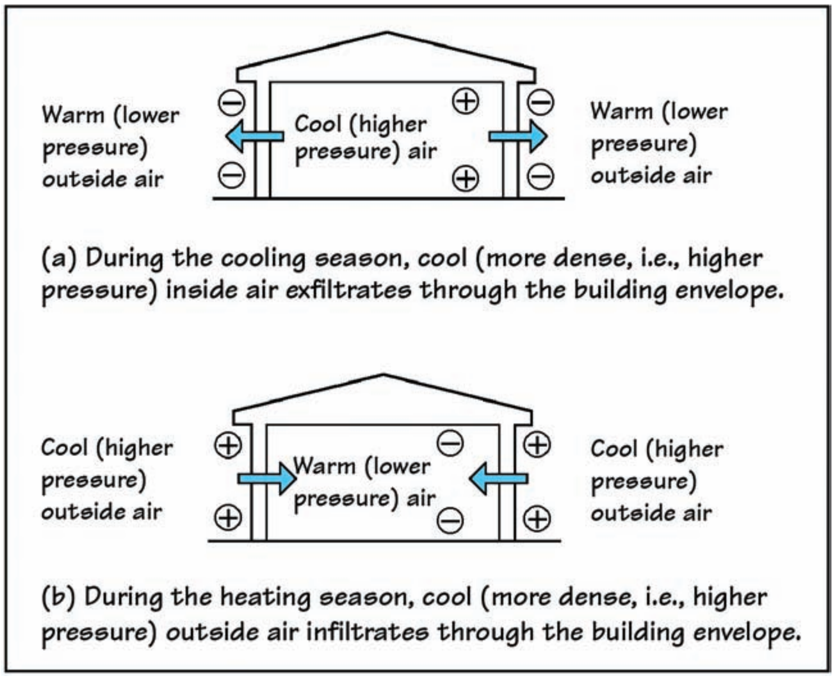

Warm (lower pressure) outside air
Cool (higher pressure) air
Warm (lower pressure) outside air
(a) During the cooling season, cool (more dense, i.e., higher pressure) inside air exfiltrates through the building envelope.
Cool (higher pressure) outside air
Warm (lower pressure) air
Cool (higher pressure) outside air
(b) During the heating season, cool (more dense, i.e., higher pressure) outside air infiltrates through the building envelope.

FIGURE 6.5 Air leakage (infiltration and exfiltration) through a building due to the temperature difference between the inside and the outside air. The plus (+) sign indicates relatively greater pressure, and the negative (−) sign indicates lower pressure.

(Chapter 9). Weather stripping made from a resilient, compressible material, is used to seal gaps around operable components.

6.3 AIR DIFFUSION CONTROL

In addition to controlling air leakage through the envelope (using sealants, gaskets, and weather stripping), we also need to reduce air diffusion through the envelope's material(s). This is achieved by using an air (diffusion) barrier in the envelope. Because an air diffusion barrier must allow water vapor to pass through it (explained in Section 6.8), it cannot be entirely impermeable to air. Therefore, it is not really an air barrier, but a retarder. However, the term commonly used in the literature (e.g., in the International Energy Conservation Code) is *air barrier*.

AIR BARRIER—A REQUIREMENT OF THE INTERNATIONAL ENERGY CONSERVATION CODE (IECC)

A well-documented study [Ref. 6.1] by the Engineering Laboratory of the U.S. National Institute of Standards and Technology (NIST) has shown that the use of air barriers in commercial buildings leads to HVAC energy savings of 3% to 36% in heating climates and 10% to 15% in cooling climates, as compared with the buildings that were without air barriers. In residential buildings, the corresponding energy savings are even greater. Therefore, the IECC requires that an air barrier be used on the opaque parts of the exterior walls framed in wood or cold-formed steel.

Air barriers are not required in roofs of buildings because most leakage sites occur in the walls of the envelope, Figure 6.6. Additional reasons for not using air barrier in roofs are: (a) roofs have a much smaller surface area than the walls—a difference that increases with increasing building height—and (b) waterproofing materials used on roofs are good air barriers.

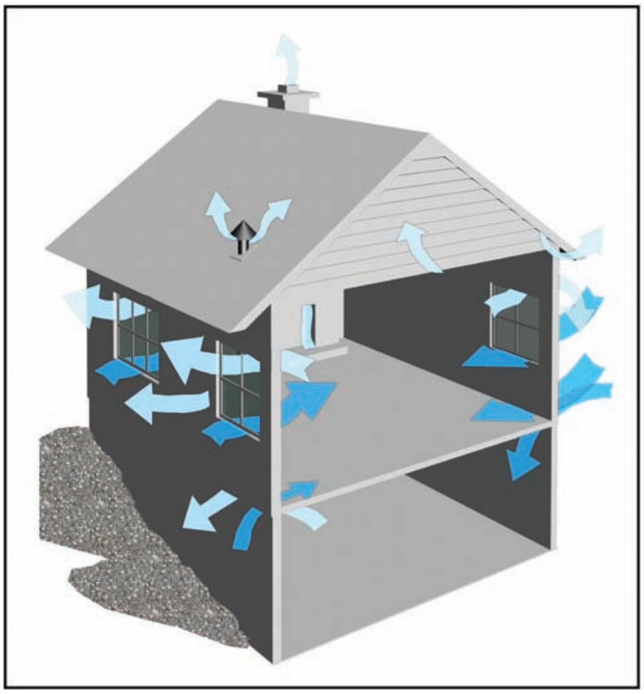


FIGURE 6.6 Typical leakage sites in a wood frame or cold-formed steel (CFS) frame building. Notice that most leakage sites in a building are in the walls.

IMPORTANT PROPERTIES OF AN AIR BARRIER AND ITS TYPES

An air barrier consists of either: (i) a sheet membrane or (ii) a liquid-applied film. The membrane or the film is applied on the outside face of the exterior wall, immediately behind the exterior cladding, Figure 6.7. Therefore, an air barrier is required to perform the following three functions:

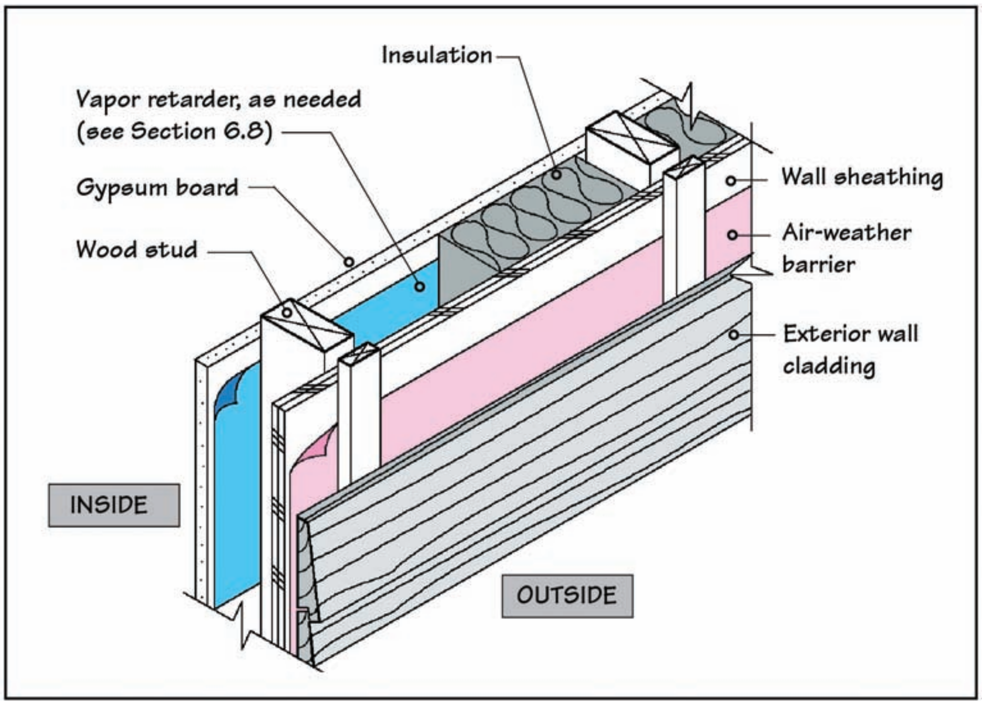


FIGURE 6.7 Location of an air-weather barrier in a wall assembly framed with wood or cold-formed steel (CFS).

i. **Air Impermeability:** An air barrier should allow little or no air to pass through, that is, it should be almost impermeable to air. (See margin note for the code mandated maximum permissible air permeability of an air barrier.)

ii. **Water Resistivity—Air Barrier as Air-Weather Barrier:** An air barrier must be water resistive (hydrophobic), that is, not allow rainwater penetration. Although exterior cladding should be impervious to rainwater, most exterior cladding materials are not entirely impervious. They allow the passage of rainwater, particularly from a sustained and severe thunderstorm. Therefore, an air barrier, being immediately behind the exterior cladding, must function as a water-resistive barrier, to prevent rainwater proceeding further into the assembly. In this role, it acts as a second line of defense against rainwater penetration; the first line of defense being the exterior cladding. Thus, an air barrier is, in fact, an air-water barrier, generally referred to as an *air-weather barrier*. The term "weather" implies rainwater.

iii. **Vapor Permeability:** An air-weather barrier should be vapor permeable, that is, allow water vapor to pass through. The permeability to water vapor is referred to as the air barrier's *breathability*. (See Section 6.8 for the reasons why an air barrier must be vapor permeable.)

NOTE

Maximum Permissible Air Permeability of an Air Barrier

Per the 2015 International Energy Conservation Code (IECC), the air permeability of an air barrier should not exceed 0.004 cfm/ft^2 [0.02 L/(s-m^2)] under an air pressure difference of 1.57 psf [75 Pa] when tested per ASTM E 2178. An unpainted $\frac{1}{2}$-in.-thick gypsum board, $\frac{3}{8}$-in.-thick plywood, or $\frac{3}{8}$-in.-thick oriented strandboard meets this requirement.

Note: "psf" stands for pounds per sq ft; "cfm/ft^2" stands for cubic feet per minute per sq ft; "L/(s.m^2)" stands for liters per second per sq meter.

SHEET MEMBRANE AIR-WEATHER BARRIER

One of the commonly used sheet membrane air-weather barrier is a 5- to 10-mil-thick plastic sheet that is wrapped over the exterior walls before installing the exterior wall cladding. The air-weather barrier sheet is microperforated. The microperforations allow very little air to pass through but provide a high degree of permeability to water vapor. Depending on the manufacturer, a membrane air-weather barrier is made from a perforated plastic sheet or plastic fibers that are either woven or spunbonded into a sheet.

Figure 6.8 shows a membrane air-weather barrier, wrapped over the entire exterior walls of wood or cold-formed steel frame buildings. It is fastened to exterior wall sheathing with cap nails, and the joints between the membranes are lapped and sealed with a self-adhesive tape. To reduce the number of joints, air-weather barriers are made in long, wide rolls; the roll width generally covers a one-story height.

Because of its low air permeability and continuity, a properly installed air-weather barrier membrane precludes the need to seal the joints between individual wall sheathing panels. An air-weather barrier is, therefore, effective against both air leakage and air diffusion.

Another commonly used sheet membrane air-weather barrier consists of a self-adhering, peel-and-stick membrane. Before adhering the membrane, the sheathing is treated with a primer, Figure 6.9. Because the membrane is not nailed but fully adhered to sheathing, it is not prone to tearing from strong winds, which a nailed membrane is until it is covered over

NOTE

$$1 \text{ mil} = \frac{1}{1{,}000} \text{ in.} = 0.001 \text{ in.}$$

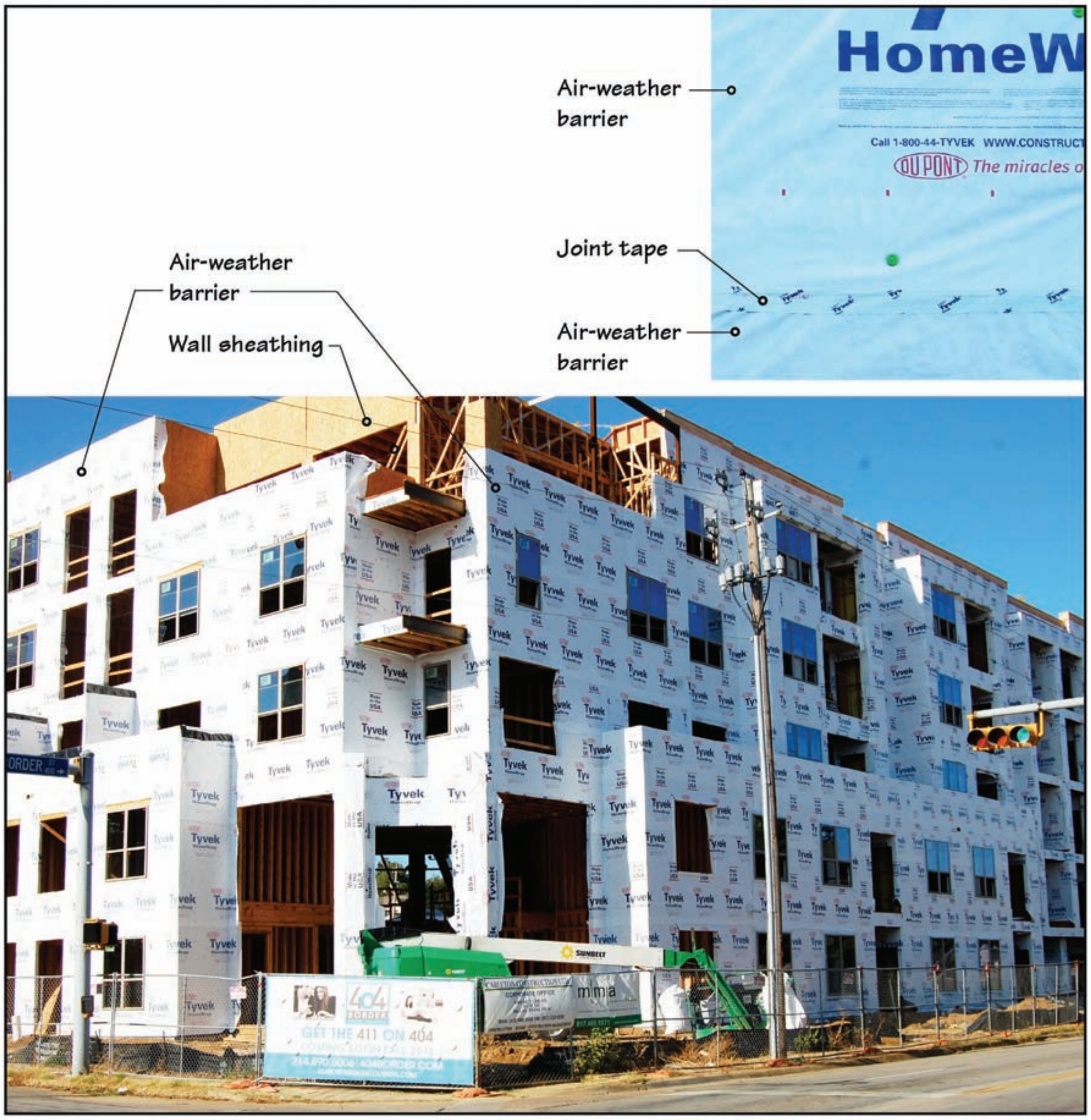

Air-weather barrier
Joint tape
Air-weather barrier
Air-weather barrier
Wall sheathing

FIGURE 6.8 A membrane air-weather barrier wrapped over the exterior wall sheathing of a five-story wood frame apartment building. The photograph was taken while the installation of air-weather barrier was in progress. After completing the installation of the air-weather barrier over all of the exterior wall sheathing, exterior cladding will be installed. The top (magnified part) of the air-weather barrier shows the self-adhering tape between its joints.

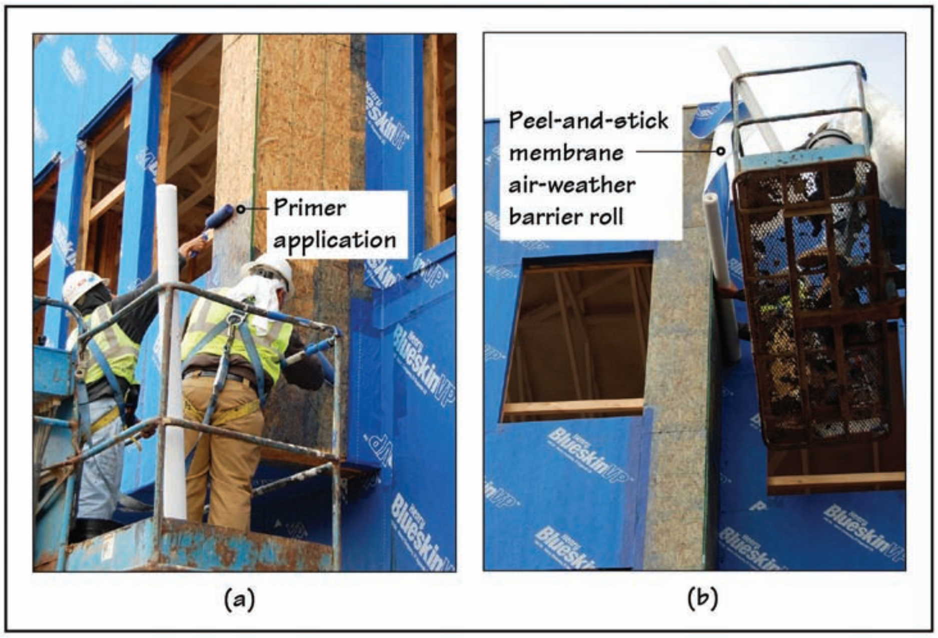

Primer application
Peel-and-stick membrane air-weather barrier roll
(a)
(b)

FIGURE 6.9 A membrane air-weather barrier adhered to sheathing. **(a)** The primer being rolled on to oriented strandboard (OSB) sheathing. **(b)** Peel-and-stick membrane air-weather barrier is adhered to sheathing after it has been primed.

by exterior cladding, which can take weeks or months. It also does not need any taped joints because the sheets are overlapped at seams.

While the membrane of Figure 6.9 is field-adhered to sheathing, that shown in Figure 6.10 consists of the membrane that is factory-adhered to sheathing panels, saving on-site labor. The joints between sheathing panels are taped after their installation.

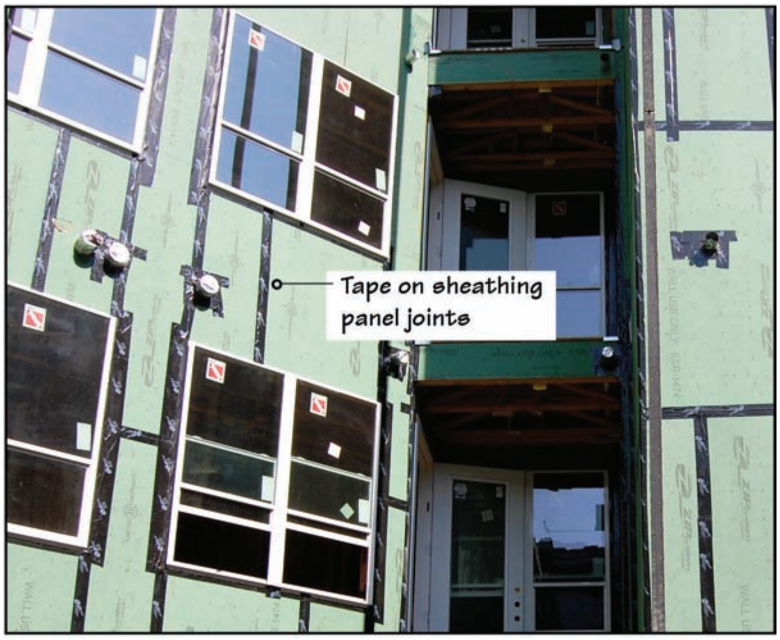


FIGURE 6.10 In this wood-frame structure, the OSB sheathing consists of a factory-adhered membrane air-weather barrier. The joints between sheathing panels are taped.

LIQUID-APPLIED FILMS AS AIR-WEATHER BARRIERS

Sheet membrane air-weather barriers are generally used on walls with exterior sheathing that is either nailable (such as oriented strandboard or plywood) or to which a membrane can be adhered. They cannot be used on nonnailable exterior wall surfaces, such as gypsum sheathing, concrete, or masonry walls. In such situations, a liquid air-weather barrier is used, which is generally rolled on, Figure 6.11.

SEALING THE EXTERIOR WINDOW AND DOOR PERIMETER

Despite the use of the air-weather barrier, the joints between the wall and the perimeter of a window (or door) can leak air (see the arrows in Figure 6.6). Depending on the type of detail around the jamb, these joints are sealed with self-adhering perimeter tapes and sealants, Figure 6.12.

AIR LEAKAGE AND DIFFUSION—ASSEMBLY PROPERTIES

The control of air movement is not obtained merely by add-on air barriers (membranes or liquid films). All components of the assembly participate in this process, some more, some less. Therefore, if the assembly is inherently impermeable to air, add-on air barriers are unnecessary. Examples of such assemblies include those with foamed-in-place insulation (see Figure 5.43, Chapter 5) and SIP assemblies (Chapter 17). In these assemblies, the insulation, with its closed-cell structure, has very low air permeability and clings snugly to framing cavities. However, such assemblies generally require a water-resistive membrane (weather barrier).

Other assemblies belonging to this category are insulated metal panels and glass-aluminum curtain walls. Because both metal and glass are impermeable to air, these assemblies only need leakage control by joint seals and gaskets; diffusion control (through the use of an air barrier) is not needed.

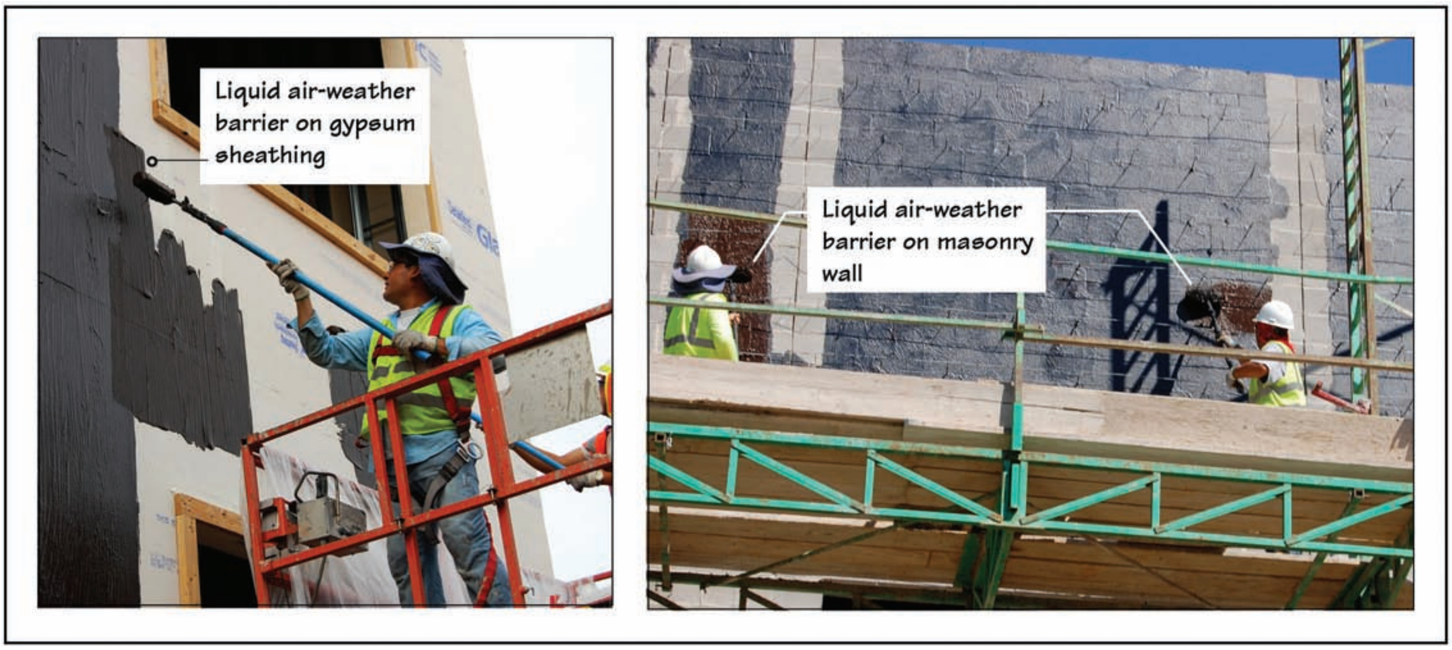

Liquid air-weather barrier on gypsum sheathing
Liquid air-weather barrier on masonry wall

FIGURE 6.11 Liquid air-weather barrier application on gypsum sheathing and masonry wall.

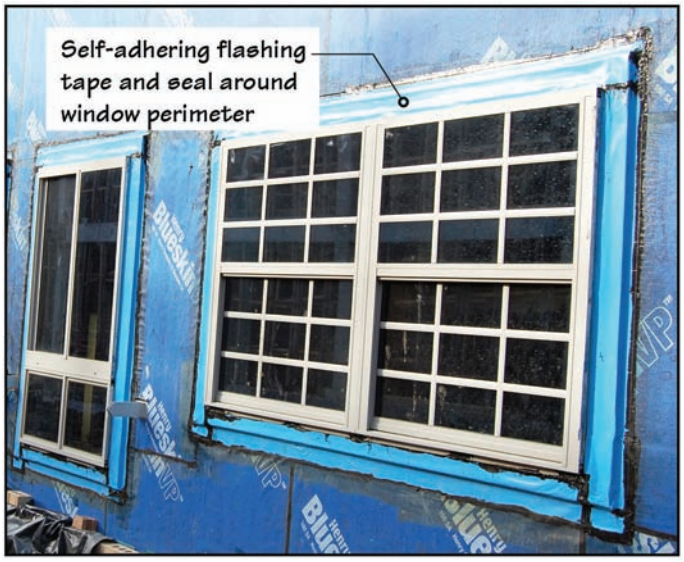

Self-adhering flashing tape and seal around window perimeter

FIGURE 6.12 Self-adhering flashing tape over air-weather barrier at window sill and jambs, and below window head prevents air and water passage between window and wall opening.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. Leakage and diffusion of a gas (such as air or water vapor) through a building envelope are two different mechanisms because
   - **a.** leakage occurs through holes, cracks, and openings in the envelope, while diffusion occurs through the body of envelope component or its material(s).
   - **b.** leakage occurs through the body of the component or material(s) of the envelope, while diffusion occurs through holes, cracks, and openings in the envelope.
   - **c.** diffusion does not occur through a building envelope while leakage does.
   - **d.** leakage refers to water leaking through the envelope (such as rainwater or subsoil water) and diffusion refers to the passage of water vapor through the envelope.
   - **e.** none of the above.
2. Although leakage and diffusion are two separate mechanisms, their impact on the performance of the envelope is the same.
   - **a.** True
   - **b.** False
3. Air leakage through a building envelope is a function of
   - **a.** the area of holes, cracks, and openings in the envelope.
   - **b.** wind speed.
   - **c.** materials of which the component is made.
   - **d.** all of the above.
   - **e.** (a), (b), and the inside-outside air temperature difference.
4. A membrane air barrier is
   - **a.** fastened to sheathing on site.
   - **b.** adhered to sheathing on site.
   - **c.** factory-adhered to sheathing panels.
   - **d.** any one of the above.
5. A wrap-type, membrane air barrier is available in many varieties, but in all of them, it is made from
   - **a.** an unperforated plastic sheet.
   - **b.** a perforated plastic sheet.
   - **c.** an asphalt-coated paper.
   - **d.** any one of the above.
   - **e.** (a) or (c).
6. Liquid-applied air barriers and membrane air barriers can be used interchangeably.
   - **a.** True
   - **b.** False
7. An air barrier is generally placed
   - **a.** toward the warm side of the envelope assembly.
   - **b.** toward the cold side of the envelope assembly.
   - **c.** on the exterior face of interior gypsum board.
   - **d.** on the exterior face of an exterior sheathing.
   - **e.** (b) or (c).
8. An air barrier is generally used on
   - **a.** the walls.
   - **b.** the ceiling.
   - **c.** the roof.
   - **d.** all of the above.
9. The primary purpose of sealants and weatherstripping is to
   - **a.** reduce vapor diffusion through the envelope.
   - **b.** reduce air leakage through the envelope.
   - **c.** reduce air diffusion through the envelope.
   - **d.** all of the above.
   - **e.** (a) and (b).
10. The use of membrane or liquid air barriers is required in the envelope of all heated or cooled buildings.
    - **a.** True
    - **b.** False
11. Breathability of an air barrier refers to its
    - **a.** permeability to air, water vapor, and water.
    - **b.** permeability to air and water vapor.
    - **c.** permeability to air.
    - **d.** permeability to water.
    - **e.** none of the above.
12. In addition to being a barrier to the passage of air, an air barrier must also function as a barrier to the passage of
    - **a.** noise.
    - **b.** water vapor.
    - **c.** both noise and water vapor.
    - **d.** subsoil water.
    - **e.** rainwater.

6.4 WATER VAPOR IN AIR

Almost all air contains some water vapor. Absolutely dry air, that is, air without water vapor, is rare. It is used in insulating glass units (see Chapter 30) and in laboratories for special purposes. Water vapor content in outside air is usually higher in coastal areas than inland locations.

Like air, water vapor is a gas. Consequently, it exerts pressure on the surfaces of the enclosure containing it. However, although air and water vapor are thoroughly mixed together, the pressure exerted by water vapor is independent of that exerted by air. In other words, air pressure and vapor pressure act separately on enclosure surfaces, Figure 6.13. This fact has an important consequence:

> *The diffusion of air and the diffusion of vapor through a building envelope are independent of each other and are controlled by their own individual pressure differences across the envelope. In other words, the diffusion of air is related to the air pressure difference across the envelope, and the diffusion of vapor is similarly related to the vapor pressure difference.*

MOVEMENT OF WATER VAPOR THROUGH ASSEMBLIES

Like air, vapor has two means of migrating through a building assembly:

- Vapor leakage (through holes and cracks in the assembly)
- Vapor diffusion (through the body of the assembly)

Because air and water vapor are thoroughly mixed, vapor and air leak through the envelope together. Controlling air leakage also controls vapor leakage.

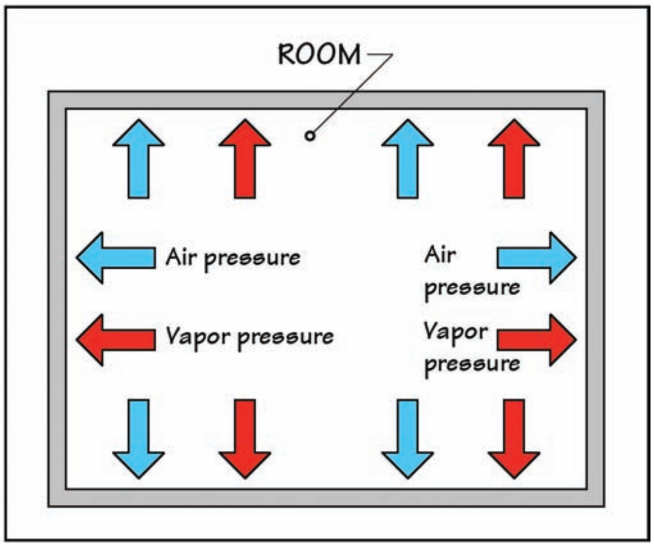


FIGURE 6.13 Although thoroughly mixed together, air and water vapor exert pressure on the boundaries of a room independent of each other so that their abilities to diffuse through the building envelope are not related to each other. This fact is per Dalton's Law of Partial Pressures.

Vapor diffusion, however, is different. As stated in Section 6.1, diffusion occurs through the material(s) of the assembly. It is a function of the vapor pressure difference across the material (or assembly), not the air pressure difference. Because air pressure and vapor pressure act independently of each other, air permeability and vapor permeability are not related to each other. That is why it is possible to make an air barrier, which allows very small amount of air to permeate through but is highly permeable to water vapor.

Not just air barriers but, in general, all *building assemblies are more vapor permeable than air permeable*. This means that water vapor can pass (leak or diffuse) through walls and roofs with greater ease than can air. The reason is that the vapor pressure difference between the inside and the outside is generally much higher than the corresponding air pressure difference. This fact explains why it is easy to make air barriers with high vapor permeability (breathable). (In Section 6.8, we will see why air barriers need to be vapor permeable.)

EXPAND YOUR KNOWLEDGE

Why Water Vapor Can Flow Through an Assembly With Greater Ease Than Air

Typical Inside-Outside Air Pressure Difference

As stated in Section 3.5 (Expand Your Knowledge section), the pressure difference between the inside and the outside air in low-rise buildings is approximately $(V/20)^2$, where the pressure difference is in pounds per square foot (psf) and V is the outside wind speed in miles per hour (mph). Thus, if V = 20 mph (a fairly windy condition), the air pressure difference between the inside and outside = 1.0 psf. On a moderately windy day with 10 mph wind speed, the corresponding air pressure difference is only 0.25 psf.

Typical Inside-Outside Vapor Pressure Difference

Vapor pressure is related to the amount of water vapor present in air. Air cannot contain an unlimited amount of water vapor. When the air contains the maximum amount of water vapor it can possibly hold, it is referred to as *saturated air*, and the corresponding vapor pressure is referred to as the *saturation vapor pressure*. The saturation vapor pressure increases with air temperature, as shown in the accompanying table. Because the relative humidity (RH) of air is directly related to the saturated air, the vapor pressure of air can be obtained by:

Vapor pressure of air = (RH/100)(vapor pressure of saturated air)

SATURATION VAPOR PRESSURE AS A FUNCTION OF AIR TEMPERATURE

Temperature (°F)	Saturation vapor pressure (psf)
10	4.5
30	11.5
50	25.5
70	52.5
90	100.5

From the table shown, if the air temperature = 70°F and RH = 45%, the vapor pressure of air = (45/100)52.5 = 23.6 psf. Similarly, for air at 10°F and 80% RH, the vapor pressure = (0.80)(4.5) = 3.6 psf. These two estimates of vapor pressure are typical inside and outside conditions, respectively, in cold climates during the heating season, giving a typical inside-outside vapor pressure difference = (23.6 − 3.6) = 20.0 psf.

Compare this vapor pressure difference of 20 psf with the typical air pressure difference of approximately 0.25 psf. For the air pressure difference to equal 20 psf, the wind speed must be

(Continued)

EXPAND YOUR KNOWLEDGE (*Continued*)

approximately 90 mph—an extremely rare occurrence. Summarizing, therefore:

It is because of the generally prevailing large vapor pressure difference across the building envelope that water vapor flows through the envelope much more easily than air.

Note that the RH of air of about 45% is the one commonly maintained in mechanically controlled interior environments. Air with a high RH ($\geq 70\%$) feels moist, promotes fungal growth, and is uncomfortable and unhealthy. Air with a low RH ($< 30\%$) dries human skin, creates static electricity in carpets, and aggravates respiratory problems.

NOTE

Important Fact About Vapor Migration

Vapor flows from the warm side to the cold side of the envelope. Thus, in cold climates, vapor tends to flow from the inside to the outside. In warm, humid climates, vapor tends to flow from the outside to the inside. In other words, heat flow and vapor flow are generally in the same direction.

NOTE

Dew Point and Vapor Impermeability of the Surface Necessary for Condensation

Note that condensation occurs only on surfaces through which water vapor cannot pass (permeate). In other words, water vapor will continue to move freely until it encounters a surface that interrupts its movement. At that location, condensation of vapor is possible, provided that the temperature of the surface is $\leq$ air's dew point (DP).

Thus, because window glass is impermeable to vapor, condensation may occur on it if its temperature is $\leq$ DP of surrounding air. Condensation does not occur in an air space even if its temperature is below the DP.

6.5 CONDENSATION OF WATER VAPOR

Consider air at a certain temperature and relative humidity (RH). If no moisture is added to or subtracted from this air and its temperature is decreased, its relative humidity will increase. If the decrease in temperature continues, a temperature will be reached at which the RH of the air is 100%. The temperature at which the air's RH becomes 100% (i.e., when the air becomes saturated) is called the air's *dew point temperature*, or simply the *dew point* of air. If the temperature of the air is decreased below the dew point, the water vapor in air converts to (liquid) water—a phenomenon known as *condensation*.

Condensation occurs commonly in nature. In heated buildings, condensation is often observed during the winter on the inside surface of a window glass. Such condensation is more pronounced in more humid interiors, such as indoor swimming pools, aerobic centers, bathrooms, and kitchens.

CONCEALED CONDENSATION AND SURFACE CONDENSATION

Apart from condensing on the surfaces of a window glass or any other cold surface, warm interior air can also condense inside a wall or roof assembly. If the vapor can move into a wall or roof assembly, it will condense where the temperature of the assembly is at or below the dew point of the migrating vapor. The condensation of vapor inside an envelope assembly is referred to as *concealed condensation*, as opposed to *surface condensation*, which occurs on the envelope's surface, such as a window glass.

Although both surface and concealed condensation are undesirable, the concealed condensation causes more problems. As stated earlier, concealed condensation wets the interior of an assembly, accelerating metal corrosion, wood decay, mold and fungi growth, and other problems. Therefore, the control of concealed condensation is particularly important.

Note, however, that water vapor by itself is not damaging to a building assembly. It becomes damaging when it converts to water.

6.6 VAPOR DIFFUSION AND CONTROL OF CONDENSATION

Surface condensation can be prevented by simply increasing the R-value of the assembly. The increase in the R-value of the assembly increases the temperature of the interior surface during winter, reducing the potential for condensation at the interior surface. Condensation occurs on the inside surface of a single glass sheet during winter because its R-value is quite low (R=1). If the single glass sheet is replaced by an insulating glass unit (with an R-value of, say, R-3 or R-4), condensation on the inside glass will not occur unless the interior air is very humid and/or the outside air temperature is very low.

In general, if the R-value of the envelope assembly is low, the dew point of air occurs at the surface of the envelope, leading to surface condensation. If the R-value of the envelope assembly is raised, the dew point shifts to within the assembly, Figure 6.14. This leads to concealed condensation, which should be avoided. (See Principles in Practice at the end of this chapter to determine the location of the dew point in an envelope assembly.)

CONTROL OF CONCEALED CONDENSATION—THE USE OF A VAPOR RETARDER

Concealed condensation occurs only if the water vapor is able to enter the envelope assembly and is then unable to exit. Therefore, a two-part strategy is used to control concealed condensation.

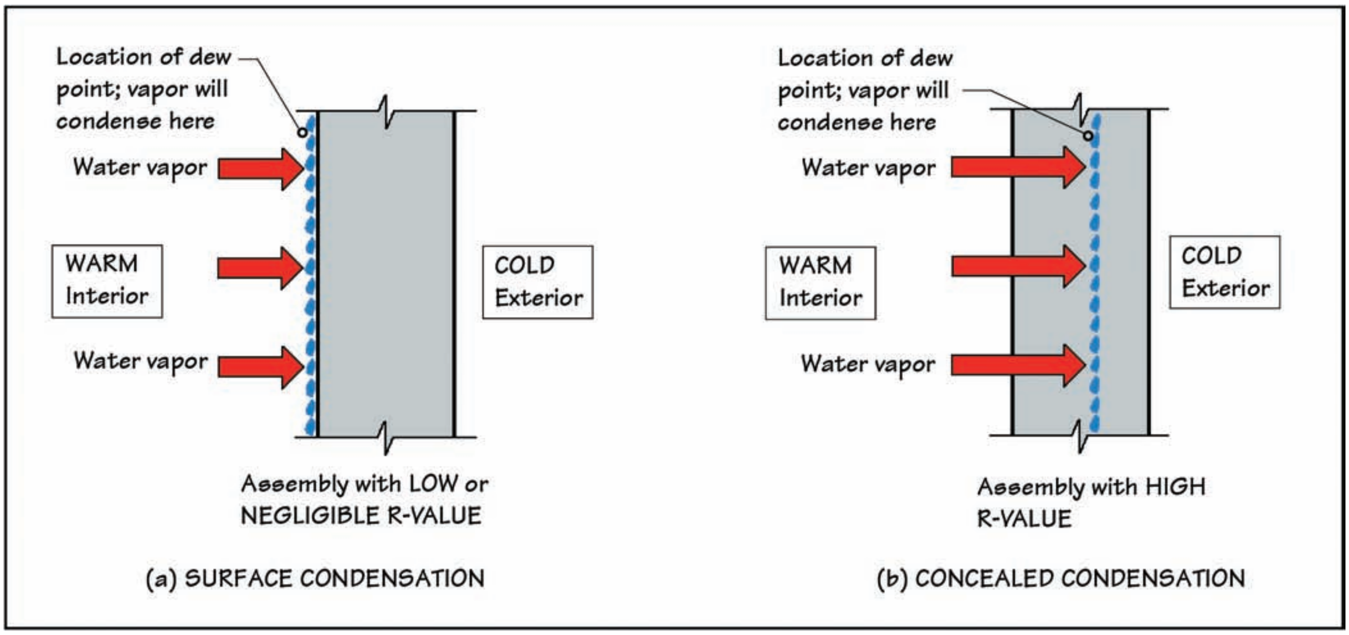

Location of dew point; vapor will condense here
Water vapor
WARM Interior
Water vapor
COLD Exterior
Assembly with LOW or NEGLIGIBLE R-VALUE
(a) SURFACE CONDENSATION
Location of dew point; vapor will condense here
Water vapor
WARM Interior
Water vapor
COLD Exterior
Assembly with HIGH R-VALUE
(b) CONCEALED CONDENSATION

FIGURE 6.14 The effect of the R-value of an assembly on the location of dew point during a heating season. **(a)** If the assembly has a low or negligible R-value (such as a single sheet of glass), the interior surface will be cold. Consequently, the dew point is likely to occur on the interior surface of the assembly where the warm interior air will condense (see Example 6.1 in Principles in Practice at the end of this chapter). **(b)** If the assembly has a high R-value, the interior surface will be warm. Therefore, the dew point will occur somewhere inside the assembly (see Example 6.3 in Principles in Practice at the end of this chapter). Note that the condensation will occur only if the interior vapor can permeate (leak or diffuse) into the assembly. If vapor cannot permeate into the assembly, there will be no condensation within such assembly.

1. The first part of the strategy is to prevent the entry of water vapor into the assembly. This is achieved by using a vapor barrier in the envelope. A vapor barrier is a material that is impermeable to vapor. It is also impermeable to air because if air leaks through it, so will vapor. Thus, a vapor barrier is both an air barrier and a vapor barrier. Note that the term *vapor retarder* is more appropriate, because most commercial vapor barriers are not absolutely vapor impermeable. The term used in the International Building Code (IBC) is also "vapor retarder".
2. The second part of the strategy, discussed in Section 6.8, is to facilitate any vapor that has entered the assembly to escape freely to the outside.

6.7 MATERIALS USED AS VAPOR RETARDERS

The rate at which water vapor diffuses (i.e., permeates) through a material is measured by its permeability. The measure of vapor permeability is called the *permeance*, or simply the *perm*. A material with a higher perm value (or rating) is more vapor permeable. If the perm rating is zero, the material is impermeable to vapor. Such a material is a (perfect) vapor barrier provided that it is free of holes, cracks, and unsealed joints.

Apart from being a property of the material, the perm rating is a function of the material's thickness. A greater thickness of the same material has a lower perm rating. Therefore, when the perm rating is given, the thickness of the component must be stated. The perm ratings of selected materials (in the U.S. system of units) are given in Table 6.1. For instance, the perm rating of a 4-mil-thick polyethylene sheet is 0.08; a 6-mil-thick polyethylene sheet's perm rating is 0.06.

CLASSIFICATION OF VAPOR RETARDERS

Vapor retarders are classified into three types:

Class I: perm rating ≤ 0.1 perm

Class II: perm rating between 0.1 perm and 1.0 perm

Class III: perm rating between 1.0 perm and 10.0 perm

Thus, from Table 6.1, a polyethylene sheet, built-up roof membrane, and aluminum foil are Class I vapor retarders. In fact, aluminum foil, if it has no perforations, has a perm rating of zero, and hence it is a (perfect) vapor barrier, as are all metals and glass. Asphalt-treated paper, referred to as *building paper* or *kraft paper*, is also a good vapor retarder (Table 6.1). Several fiberglass insulation manufacturers make fiberglass batts faced with building

TABLE 6.1 APPROXIMATE PERM RATINGS OF SELECTED MATERIALS (IN THE U.S. SYSTEM OF UNITS)

Component	Perm rating (perm)	Component	Perm rating (perm)
Aluminum foil (unpunctured)	0.0	Brick masonry, 4 in. thick with tooled mortar joints	4.0
Aluminum foil on gypsum board	0.1	Concrete block masonry, 8 in. thick with tooled mortar joints	6.0
Built-up roofing, 3- to 5-ply	0.0	Unpainted gypsum board	6.0
15-lb asphalt felt	4.0	Latex or enamel paint on gypsum board	3.0
Polyethylene sheet, 4 mil thick	0.08	Building paper, grade B	1.0
Polyethylene sheet, 6 mil thick	0.06	Exterior oil paint, 3 coats on wood	0.3–1.0
Polyethylene sheet, 8 mil thick	0.03	Commercial air barriers	15–60

Reference: Several sources.

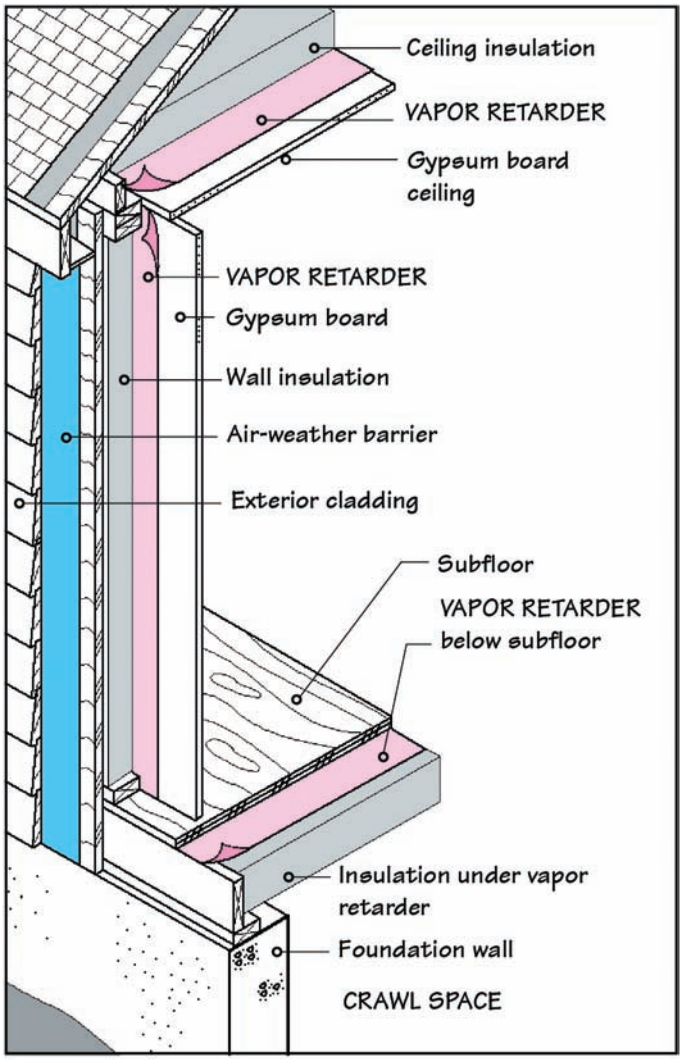


FIGURE 6.15 Per the International Building Code, a vapor retarder (Class I or II) is required on all interior surfaces of exterior walls framed with wood or cold-formed steel studs in climate zones 5, 6, 7, 8, and marine 4. The objective is to restrain the migration of interior vapor into the envelope assembly, where it could condense. For the use of vapor retarder in climate zones 1 to 4, see Section 6.8.

paper (see Figure 5.35), which qualifies as a Class II vapor retarder. Gypsum board with latex or enamel paint qualifies as a Class III vapor retarder (Table 6.1).

6.8 VAPOR RETARDERS AND CLIMATE ZONES

In cold climates, the concentration of water vapor is greater inside the building as compared with the outside, causing the interior vapor to migrate to the outside. Building codes, therefore, require that a vapor retarder be installed toward the interior side of the building envelope in cold climates, Figure 6.15. The objective is to contain the vapor within the building interior so that it will not migrate into the envelope assembly, where it could condense. To achieve this objective, all penetrations through the vapor retarder and all vapor retarder joints should be fully sealed. (Cold climates are defined by the codes as climate zones 5, 6, 7, 8, and Marine 4.)

Vapor Permeability of an Air-Weather Barrier

Because the vapor retarder is not a (perfect) vapor retarder and sealing the leaks may be imperfect, some vapor is bound to migrate into the assembly, where it may condense if not allowed to escape out of the assembly. To ensure its escape, the assembly beyond the vapor retarder is required to be vapor permeable (breathable), Figure 6.16. That is why the air-weather barrier, which is placed on the exterior face of the walls, is required to be vapor permeable.

Vapor permeability of a wrap-type air barrier is achieved through its perforations. If the air barrier is not perforated, any vapor that travels through the vapor retarder will be trapped between the vapor retarder and the air barrier and will condense there. To further facilitate the escape of vapor out of the assembly, a vented air space between the air barrier and the exterior wall cladding is desirable (see Figure 6.7).

What about the interior vapor that migrates beyond the vapor retarder into the ceiling? Because the roof cover materials are not vapor permeable (they are good vapor retarders), vapor must be removed by venting the attic space. Without adequate attic ventilation, the vapor will be trapped in the attic, where it may condense. For the same reason, the crawl space should also be ventilated.

Warm Climates and Vapor Retarder

In warm climates (particularly in warm-humid climates of Climate zones 1 and 2), the outside vapor pressure is generally much higher than the inside vapor pressure so that the vapor

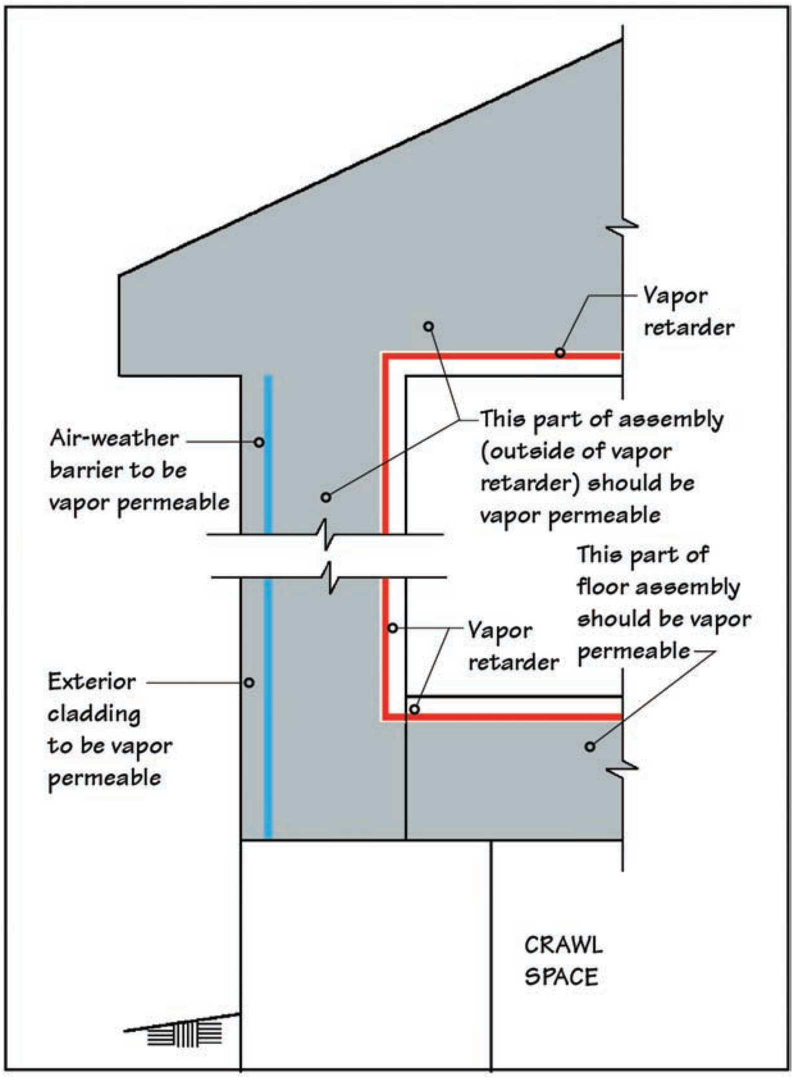

Vapor retarder
This part of assembly (outside of vapor retarder) should be vapor permeable
Air-weather barrier to be vapor permeable
This part of floor assembly should be vapor permeable
Vapor retarder
Exterior cladding to be vapor permeable
CRAWL SPACE

FIGURE 6.16 Because a vapor retarder encloses an interior space completely (as shown), interior vapor will not permeate into the envelope assembly. However, to ensure that any unintended, small amount of interior vapor, which may migrate into the envelope assembly, does not condense therein, the assembly beyond the vapor retarder should be vapor permeable (breathable).

will tend to migrate from the outside to the inside—reverse of that in cold climates. The vapor control strategy here is to allow the outside vapor to permeate through the assembly into the building interior, from where it is removed by the HVAC system. In other words, the vapor control strategy for warm climates is essentially the same as that for the cold climates, that is, not to allow the water vapor to be trapped within the assembly, where it could condense. Therefore in such climates, either the use of the vapor retarder is not recommended, or the use of a highly permeable vapor retarder (such as Class III vapor retarder) is recommended. In mixed climates (Climate zones 3 and 4), the vapor control strategy is a mix of those used for cold and warm climates, indicated as follows.

SELECTION OF AN APPROPRIATE VAPOR RETARDER

The International Building Code gives the following prescriptions for the use of vapor retarders.

1. Climate zones 5, 6, 7, 8, and marine 4: Use Class I or II vapor retarder on the interior side of a wood frame or cold-formed steel (CFS) frame exterior walls.
2. Climate zones 3 and 4: Class I vapor retarder is not to be used on the interior side of a wood frame or cold-formed steel (CFS) frame exterior walls.
3. Climate zones 1 and 2: Class I or Class II vapor retarder is not to be used on the interior side of a wood frame or cold-formed steel (CFS) frame exterior walls.

Note from Table 6.1 that latex or enamel painted gypsum board has a perm rating of 3.0, implying that it functions as a Class III vapor retarder. Therefore, in situations where gypsum board is the interior wall finish (a standard practice on most wood and CFS frame walls), a

NOTE

Units of Vapor Permeability (Perm Rating) of Materials

U.S. System of Units:
1 perm = 1 grain of water vapor passing through 1 ft^2 of a material in 1 h under a vapor pressure difference of 1 in. of mercury. (1 lb = 7,000 grains)

SI System of Units:
1 perm = 1 mg of water vapor passing through 1 m^2 of a material in 1 second under a vapor pressure difference of 1 pascal.

NOTE

Minimum Required Vapor Permeability of an Air Barrier

Per the 2015 International Building Code, the minimum required perm rating of an air barrier is 5.0 U.S. perms. Because a Class I vapor retarder has a perm rating of ≤0.1 perm, an air barrier is, therefore, at least 50 times more vapor permeable than a Class I vapor retarder. The perm rating of commercial air-weather barriers is much greater than 5.0, making them quite vapor permeable (breathable).

separate vapor retarder is not required in Climate zones 1 to 3. Therefore, most contemporary buildings in Climate zones 1 to 3 are being designed without a separate vapor retarder. In Climate zone 4, a Class II vapor retarder (e.g., fiberglass insulation with asphalt-treated building paper) may be used.

6.9 IMPORTANCE OF ATTIC VENTILATION

Ventilating the attic is necessary for reasons other than condensation control. In cold climates, ventilation prevents the formation of ice dams at projecting roof eaves. If the attic is not ventilated, it remains relatively warm because of the entry of heat into the attic from the warm interior, but the eave overhangs are cold. This melts the snow in the middle of the roof, which freezes again at the eaves, forming ice dams, Figure 6.17(a). The problem is worse in a roof-ceiling assembly with inadequate insulation.

Ice dams can substantially increase the load at eave overhangs and gutters. They also prevent water from draining off the roof, which may cause roof leakage. Adequate ceiling insulation, coupled with ventilation of the attic, helps to eliminate ice dams as well as the buildup of water vapor, Figure 6.17(b).

Attic ventilation is also required in warm climates to reduce heat transmission from the attic into the interior of the building. The temperature of the air in an unventilated attic becomes much higher than that of the outside air because of the ability of air and the materials of the roof to store heat. This is particularly critical during the summer.

Temperature differences between the outside air and the attic air in excess of 40°F have been reported in unventilated or inadequately vented attics. The higher attic temperature increases heat transfer to the interior of the building. As shown in Figure 6.17(b), attic ventilation can be provided through openings in the soffit. The openings must be covered with a mesh or screen to prevent the entry of insects. Building codes mandate a certain minimum area of soffit vents.

Soffit ventilation is considered as *intake ventilation*. Adequate ventilation of the attic requires cross ventilation, requiring intake as well as *exhaust ventilation*. Because warm air rises, exhaust ventilation is required at a higher level in the attic. Four different alternatives are used for exhaust ventilation, Figure 6.18:

- Gable ventilators
- Ridge ventilators
- Turbine ventilators
- Gable fans

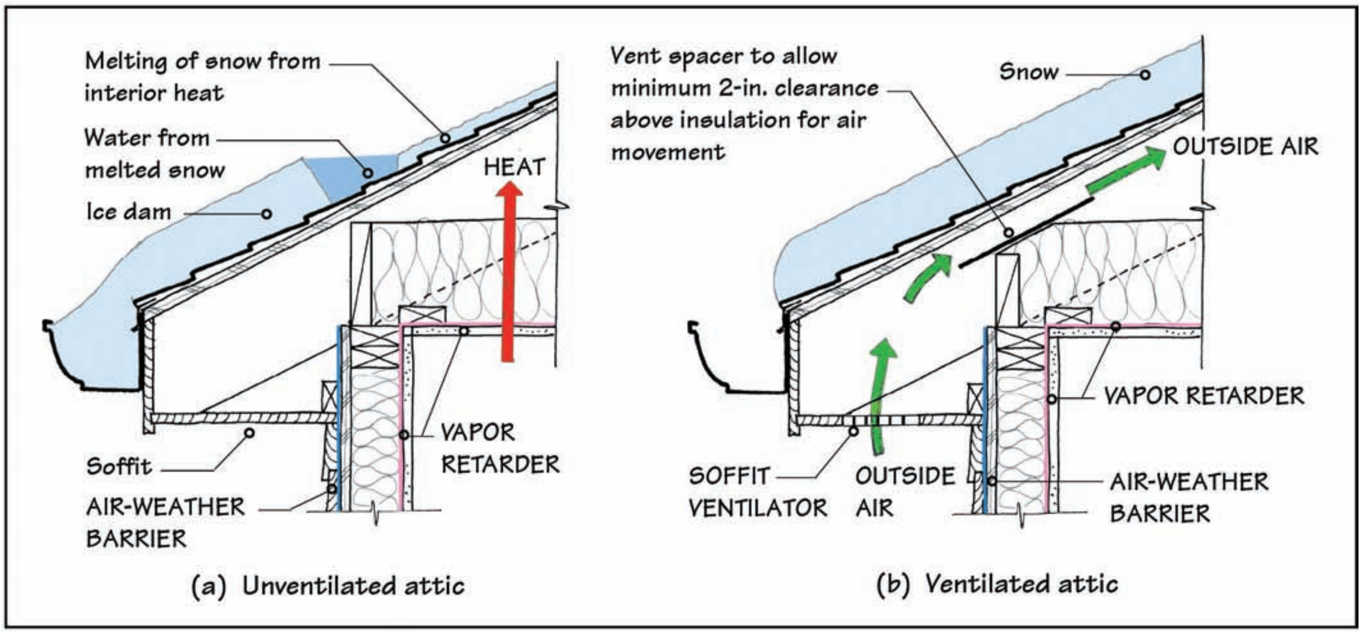


FIGURE 6.17 The effect of attic ventilation on the formation of ice dams at overhanging eave of a sloping roof.

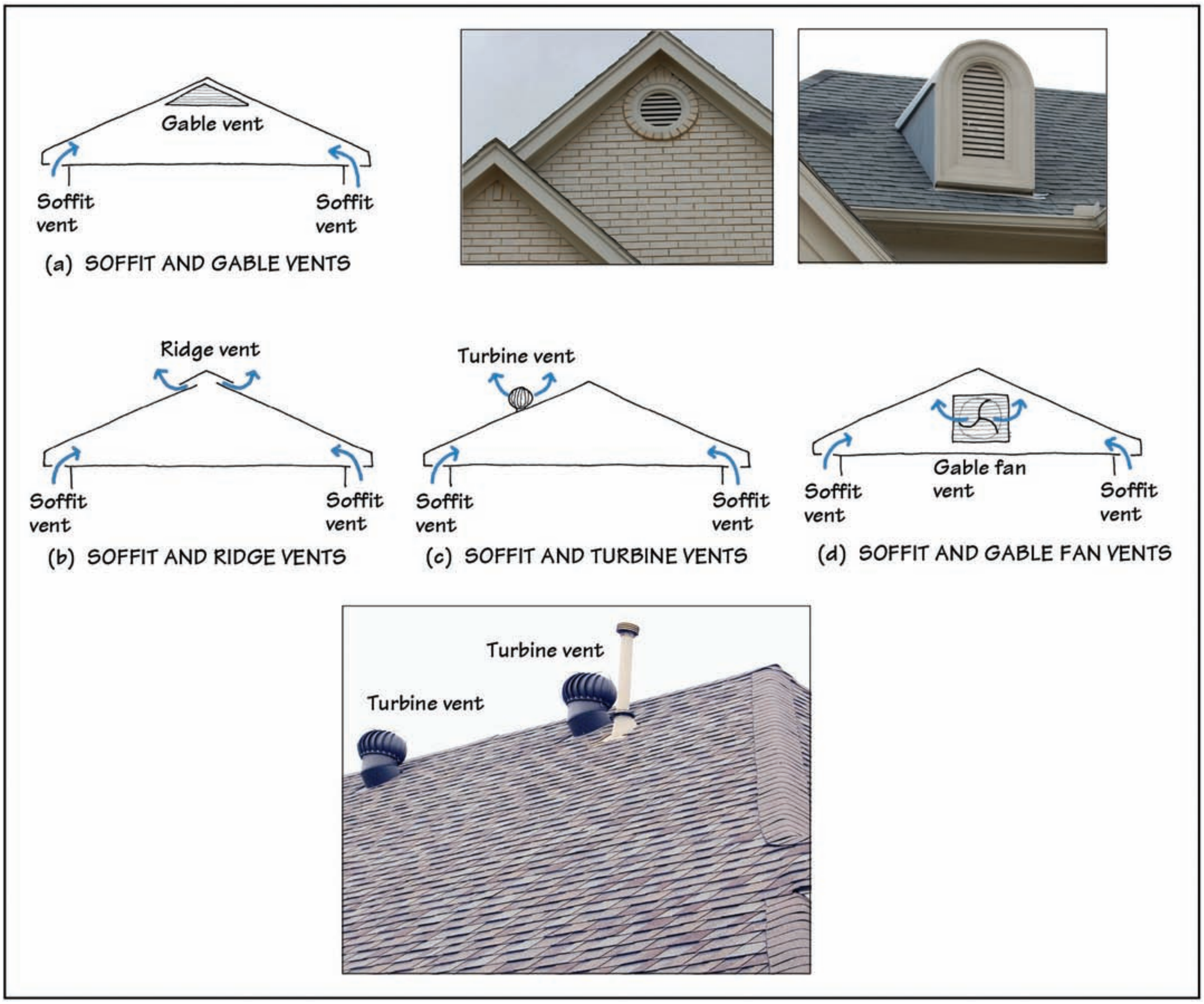

Gable vent
Soffit vent
Soffit vent
(a) SOFFIT AND GABLE VENTS
Ridge vent
Soffit vent
Soffit vent
(b) SOFFIT AND RIDGE VENTS
Turbine vent
Soffit vent
Soffit vent
(c) SOFFIT AND TURBINE VENTS
Gable fan vent
Soffit vent
Soffit vent
(d) SOFFIT AND GABLE FAN VENTS
Turbine vent
Turbine vent

FIGURE 6.18 Various alternatives of providing attic ventilation. Soffit vents function as intake ventilators, while gable vents, ridge vents, turbine vents, or gable fan vents function as exhaust ventilators. Any one of the four exhaust ventilation options may be used along with soffit vents.

EXPAND YOUR KNOWLEDGE

Vapor-Tight Construction and Attic Ventilation

Although preventing condensation in an attic by providing attic ventilation is perhaps the safest approach and one that is currently mandated by building codes, it is not without disadvantages. In extremely cold climates with frequent blowing snow and rain, venting can cause serious problems by permitting snow and rain to infiltrate the vents. Experience in cold Canadian climates has demonstrated that if indoor humidity levels are controlled and the ceiling is provided with a well-installed vapor barrier with an extremely low vapor permeability (vapor-tight construction), it is possible to prevent attic condensation without providing attic ventilation.

A major advantage of eliminating attic ventilation is that it improves the effectiveness of attic insulation. However, if attic ventilation is not provided, the problem of ice dam formation should be investigated or prevented by eliminating eave overhangs.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

13. During the heating season, the vapor pressure of the inside air in a typical dwelling in the northern United States is
- **a.** the same as the outside air.
- **b.** lower than the outside air.
- **c.** greater than the outside air.

14. The dew point of air is always
- **a.** less than or equal to the air temperature.
- **b.** greater than or equal to the air temperature.
- **c.** unrelated to the air temperature.

15. During the heating season, the vapor flow in conditioned buildings is generally from
- **a.** the inside to the outside of the envelope.
- **b.** the outside to the inside of the envelope.

(*Continued*)

PRACTICE QUIZ *(Continued)*

16. In hot, humid climates, the vapor flow in conditioned buildings is generally from
  a. the inside to the outside of the envelope.
  b. the outside to the inside of the envelope.

17. Building assemblies are generally more vapor permeable than air permeable because
  a. vapor is not really a gas.
  b. vapor has only water molecules, while air is a mixture of nitrogen and several other gases.
  c. vapor is only a small part of the air-vapor mixture.
  d. vapor molecules are heavier than air molecules.
  e. vapor pressure differential between the inside and the outside air is much greater than the corresponding air pressure differential.

18. Concealed condensation occurs inside an envelope assembly during a heating season if
  a. the interior vapor can permeate into the assembly but cannot exit it.
  b. the R-value of the assembly is low.
  c. the R-value of the assembly is high.
  d. (a) and (b).
  e. (a) and (c).

19. Perm rating is a property that measures
  a. how effectively the air diffuses through the material.
  b. how effectively water vapor leaks through the material.
  c. how effectively water vapor diffuses through the material.
  d. (a) and (b).
  e. (a) and (c).

20. Which of the following materials has the lowest perm rating?
  a. 4-in.-thick concrete wall
  b. 4-in.-thick brick wall
  c. $\frac{1}{16}$-in.-thick plastic sheet
  d. $\frac{1}{16}$-in-thick aluminum sheet
  e. All of the above materials have the same perm rating.

21. The greater is the thickness of a given material, the greater is its perm rating.
  a. True **b.** False

22. A material whose perm rating in the U.S. system of units is 0.5 perm is a
  a. Class I vapor retarder.
  b. Class II vapor retarder.
  c. Class III vapor retarder.
  d. Class IV vapor retarder.
  e. none of the above.

23. Per the International Building Code, Class I vapor retarder should only be used in wood or cold-formed steel (CFS) frame assemblies in
  a. Climate zones 1, 2, 3, 4, and 5.
  b. Climate zones 3, 4, 5, and 6, and 7.
  c. Climate zones 3, 4, 5, 6, and marine 4.
  d. Climate zones 4, 5, 6, 7, and marine 4.
  e. Climate zone 5, 6, 7, 8, and marine 4.

24. In warm climates, such as Climate zones 1 to 3, the vapor retarder may be omitted in wood or cold-formed steel (CFS) framed assemblies if the interior wall finish is a latex painted gypsum board.
  a. True **b.** False

25. A vapor retarder is perforated so that
  a. water may pass through the pores.
  b. water vapor may pass through the pores.
  c. air may pass through the pores.
  d. both air and water vapor may pass through the pores.
  e. none of the above.

26. Ventilation of an attic space is generally considered important in
  a. cold climates only.
  b. moderately cold climates only.
  c. hot climates only.
  d. all climates.
  e. none of the above.

27. Soffit vents alone are not adequate to provide attic ventilation.
  a. True **b.** False

28. When gable vents are provided to ventilate an attic space,
  a. ridge vents are also necessary.
  b. turbine vents are also necessary.
  c. soffit vents are also necessary.
  d. no other vents are necessary.

29. An ice dam is likely to occur
  a. in the middle of a sloping roof.
  b. at the eave of a sloping roof.
  c. in the middle of a flat roof.
  d. at the edge of a flat roof.

PRINCIPLES IN PRACTICE

Condensation Analysis—Where Dew Point Occurs in an Assembly

It is often necessary to determine the location of the dew point in the envelope to assess if and where condensation may occur in the assembly. In stud assemblies with fibrous insulation between studs, the concern is about concealed condensation. In glass curtain wall assemblies, commonly used in high-rise office buildings, the concern is about (interior) surface condensation.

Determining the location of the dew point requires determining the temperature variation through the assembly. A graphical representation of temperature variation is called the *temperature gradient*, which is a line passing through the cross section of the assembly. Because condensation is generally a cold-climate phenomenon, the temperature gradient line slopes down toward the outside, because the temperature is highest on the inside, and reduces gradually toward the outside of the assembly.

From Equation (5.2) in Chapter 5, we see that the amount of heat (Q) passing through an element is a function of its R-value and of the temperature drop, $(t_2 - t_1)$, across the element, that is:

$$\boxed{Q = \frac{t_2 - t_1}{R}}$$

In other words,

$$\boxed{(t_2 - t_1) = QR} \qquad \textbf{Eq. (6.1)}$$

In a multilayer assembly, the amount of heat that enters the first layer of the assembly must exit the last layer so that the amount of heat (Q) flowing through each layer of the assembly is the same, that is, constant for the entire assembly. Because Q is a constant in Equation 6.1, the temperature drop across a layer is directly proportional to the R-value of the layer, that is, the greater the R-value of the layer, the greater the temperature drop across that layer. Using Equation (6.1), it can be shown that for a multilayer assembly:

$$\boxed{\Delta = \frac{(\Delta t)R}{R_t}} \qquad \textbf{Eq. (6.2)}$$

Where, Δ = temperature drop across a layer, and R = R-value of that layer. ΔT = temperature drop across the entire assembly and R_t = R-value of the entire assembly (the sum of the R-values of all layers). As an example, consider an assembly consisting of three layers (layers 1, 2, and 3), with R-values of R-1, R-3, and R-6, respectively, so that the total R-value of the assembly = R_t = 10, Figure 6.19. Assume that the total temperature drop across the entire assembly (all the three layers), Δt = 50°F. Therefore, from Equation (6.2):

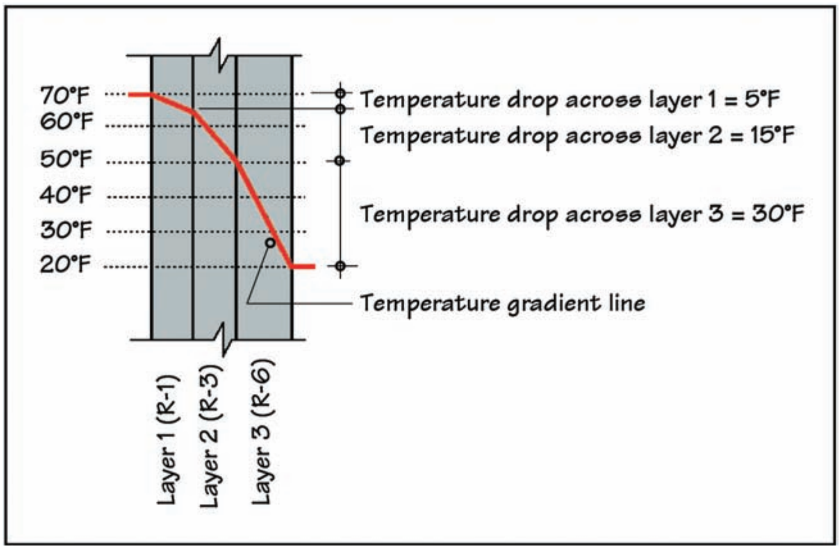

70°F
60°F
50°F
40°F
30°F
20°F
Temperature drop across layer 1 = 5°F
Temperature drop across layer 2 = 15°F
Temperature drop across layer 3 = 30°F
Temperature gradient line
Layer 1 (R-1)
Layer 2 (R-3)
Layer 3 (R-6)

FIGURE 6.19 Temperature gradient line superimposed on an assembly's cross section consisting of three layers. The thickness of each layer is based on its actual physical dimension. Note that the temperature gradient line is not a straight line.

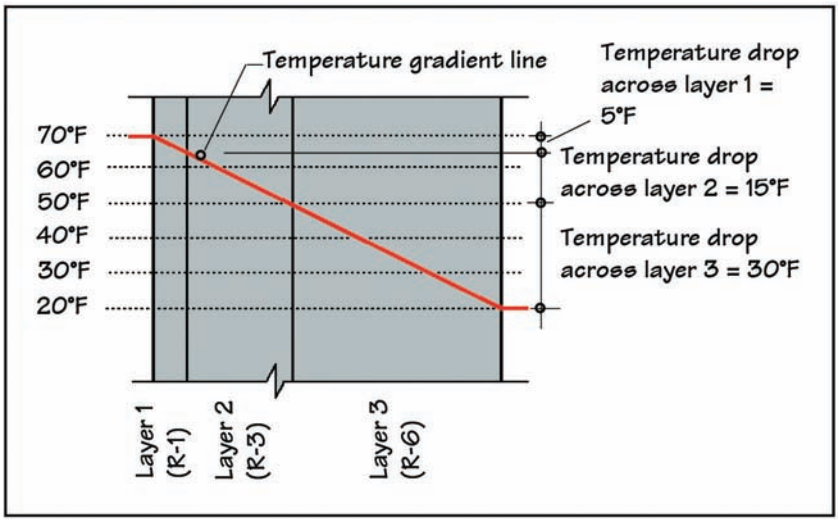

Temperature gradient line
Temperature drop across layer 1 = 5°F
Temperature drop across layer 2 = 15°F
Temperature drop across layer 3 = 30°F
70°F
60°F
50°F
40°F
30°F
20°F
Layer 1 (R-1)
Layer 2 (R-3)
Layer 3 (R-6)

FIGURE 6.20 Temperature gradient line superimposed on the cross section of the same assembly as that of Figure 6.19, but the thickness of each layer is proportional to its R-value. Note that the temperature gradient line is a straight line.

Temperature drop across layer 1 = (50)(1)/(10) = 5°F
Temperature drop across layer 2 = (50)(3)/(10) = 15°F
Temperature drop across layer 3 = (50)(6)/(10) = 30°F

The temperature gradient line for the assembly, superimposed on the assembly's cross section, is shown in Figure 6.19. The temperature gradient line is more easily obtained if the cross section of the assembly is drawn based not on the physical dimensions of each layer, but on the R-value of each layer. In that case, the temperature gradient line is one continuous straight line. The temperature gradient line of the assembly of Figure 6.19, obtained from this simplified procedure, is shown in Figure 6.20.

LOCATION OF THE DEW POINT (DP) IN THE ASSEMBLY

Once the temperature gradient line has been obtained, the dew point (DP) can be located from Table 6.2 (given at the end of this section), which provides the DP of air for various temperature and RH values. For example, the DP of air at 70°F and 30% RH, from Table 6.2, is 37°F. The following examples illustrate the procedure.

(Continued)

PRINCIPLES IN PRACTICE

Condensation Analysis—Where Dew Point Occurs in an Assembly (*Continued*)

TABLE 6.2 APPROXIMATE DEW POINT (DP) TEMPERATURE AS A FUNCTION OF AIR TEMPERATURE AND RELATIVE HUMIDITY OF AIR

	Air temperature (°F)				
RH (%)	**50**	**60**	**70**	**80**	**90**
100	50	60	70	80	90
90	47	57	67	77	87
80	44	54	64	73	83
70	40	50	60	69	79
60	36	46	55	65	74
50	33	41	50	60	69
40	27	35	45	53	62
30	21	29	37	46	54
20	13	20	28	35	43
10	6	9	13	20	27
0	This air will not condense.				

EXAMPLE 6.1

Determine the location of the DP on a glazing consisting of a $\frac{1}{4}$-in.-thick glass sheet. Assume that the inside air film (surface) resistance, $R_{si} = 0.7$, and the outside air film resistance, $R_{so} = 0.2$. Assume that the inside and the outside air temperatures are 70°F and 10°F, respectively, and the inside RH = 45%.

SOLUTION

The R-value of the glass sheet is zero. Therefore, the total R-value of the assembly considering inside and outside air films = $R_t = 0.7 + 0 + 0.2 = 0.9$. Figure 6.21 shows the temperature gradient through the assembly's cross section (the thickness of each layer is proportional to its R-value). From Table 6.2, the DP of the inside air (at 70°F and 45% RH) = 47.5°F (obtained by interpolation). From Figure 6.21, the temperature of the inside surface of the glass (approximately 23°F) is well below the DP. Therefore, condensation will occur on the inside surface of the glass.

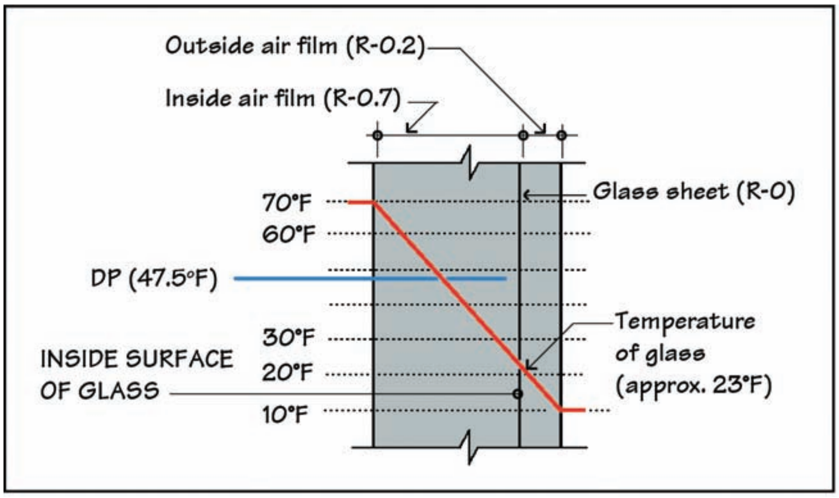


FIGURE 6.21 Temperature gradient in the assembly of Example 6.1. The thickness of each layer is proportional to its R-value. The dew point of air lies within the inside air film. Therefore, condensation will occur at the inside surface of the glass.

EXAMPLE 6.2

Determine the location of the DP for a glazing with (sealed) insulating glass units (IGU), consisting of two glass sheets, each $\frac{1}{4}$-in. thick separated by a $\frac{1}{2}$-in.-wide air space. Assume that the inside air film resistance, $R_{si} = 0.7$, the R-value of the $\frac{3}{8}$-in. air space = 1.0, and the outside air film resistance, $R_{so} = 0.2$. Assume that the inside and the outside air temperatures are 70°F and 10°F, respectively, and the inside RH = 45%. (For an illustration of an IGU, see Figure 30.19.)

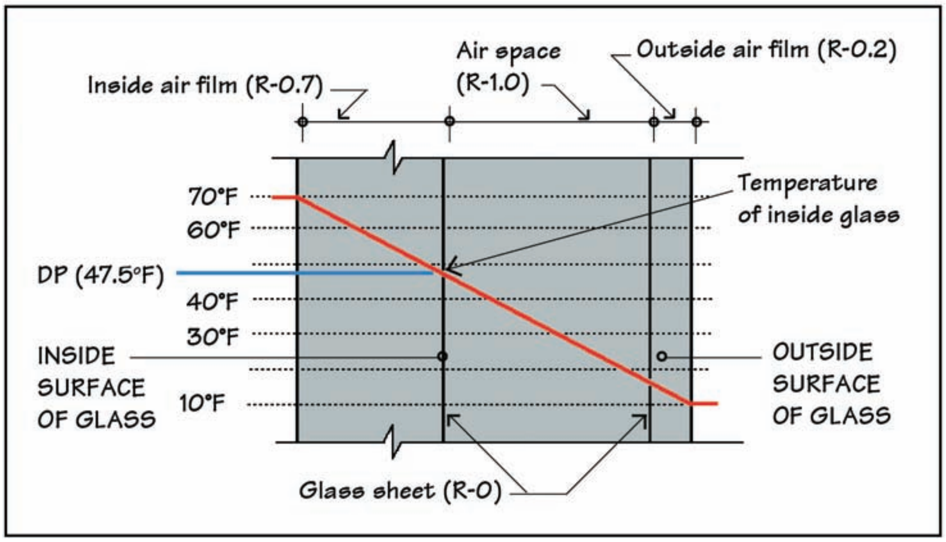

Inside air film (R-0.7)
Air space (R-1.0)
Outside air film (R-0.2)
Temperature of inside glass
70°F
60°F
DP (47.5°F)
40°F
30°F
INSIDE SURFACE OF GLASS
10°F
OUTSIDE SURFACE OF GLASS
Glass sheet (R-0)

FIGURE 6.22 Temperature gradient in the assembly of Example 6.2. The thickness of each layer is proportional to its R-value.

SOLUTION

$R_t = 0.7 + 1.0 + 0.2 = 1.9$. The temperature gradient through the assembly is shown in Figure 6.22. As shown, the temperature of the inside surface of the IGU is approximately 47.5°F, which is the same as the DP of the interior air. Therefore, some condensation is likely to occur on the glass. Also note that because an IGU is a sealed unit, the air (or water vapor) cannot permeate it. Therefore, there will be no condensation within the IGU.

EXAMPLE 6.3

Determine the location of the DP in the brick veneer wall assembly of Example 5.4 (Chapter 5), consisting of 2 × 4 wood studs spaced 16 in. on center. The spaces between the studs are filled with $3\frac{1}{2}$-in.-thick fiberglass insulation, as shown in Figure 6.23 (which is a copy of Figure 5.17 in Chapter 5). Assume that the inside and the outside air temperatures are 70°F and 10°F, respectively, and the inside RH = 45%.

SOLUTION

From Example 5.4 (Chapter 5), the R-values of various layers of the assembly are:

Inside air film resistance = 0.7
$\frac{1}{2}$-in.-thick gypsum board = 0.3
$3\frac{1}{2}$-in.-thick fiberglass insulation = 12.25
$\frac{1}{2}$-in.-thick oriented strandboard = 0.7
2-in.-wide air space = 1.0
$3\frac{5}{8}$-in.-thick brick veneer = 0.73
Outside air film resistance = 0.2

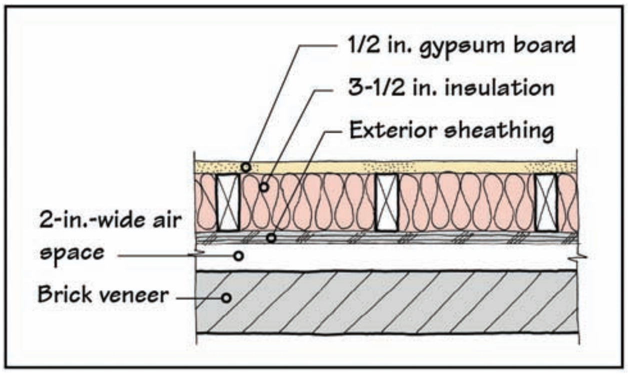

1/2 in. gypsum board
3-1/2 in. insulation
Exterior sheathing
2-in.-wide air space
Brick veneer

FIGURE 6.23 Plan of the wall of Example 6.3.

Figure 6.24 shows the temperature gradient line superimposed on the cross section of the assembly based on the R-values of layers. Note that DP (47.5°F) is located within the insulation. Therefore, condensation will occur within the insulation if inside vapor is able to permeate through it.

(Continued)

PRINCIPLES IN PRACTICE

Condensation Analysis—Where Dew Point Occurs in an Assembly (*Continued*)

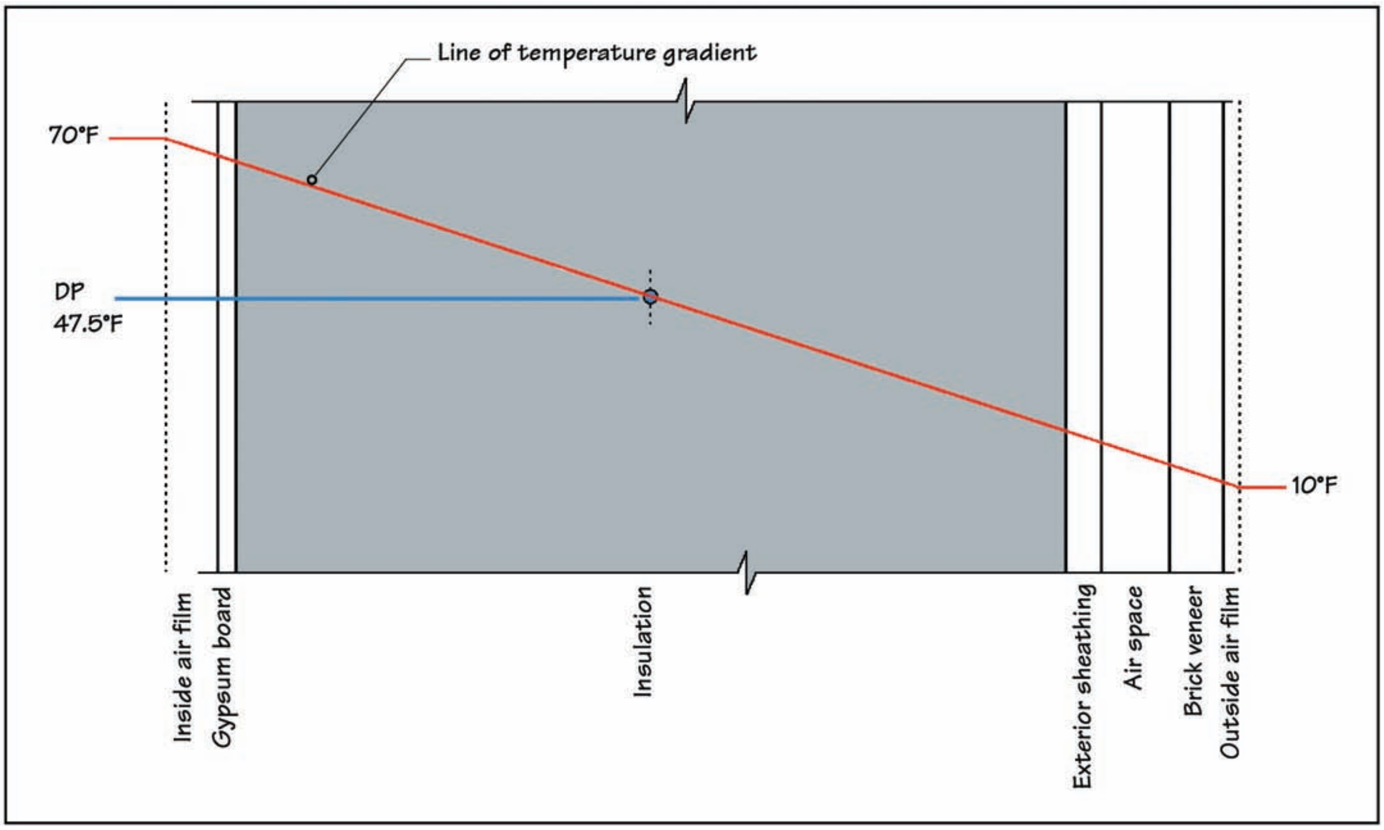


FIGURE 6.24 Temperature gradient in the wall of Example 6.3. The thickness of each layer is proportional to its R-value.

REVIEW QUESTIONS

1. Using a sketch, explain the difference between leakage and diffusion. To which material (solid, liquid, or gas) does the concept of diffusion apply?
2. Using a sketch, explain why an air barrier is called an air-weather barrier.
3. Describe the types of air-weather barriers currently used and their suitability for different situations. Explain why air-weather barrier is used only in exterior walls, not the roof.
4. Using a three-dimensional sketch, show the locations of the air barrier and vapor retarder in a wall assembly framed in wood or cold-formed steel.
5. Explain why the micro-perforations in a membrane-type air-weather barrier allow water vapor to pass through but neither (liquid) water nor air.
6. Explain the difference between surface condensation and concealed condensation. Explain in which situations these two types of condensation would occur and why.
7. Explain why it is much easier for vapor to flow through building assemblies than air.
8. Explain the difference between various classes of vapor retarders. In which climates does the building code require the use of a vapor retarder, and its class? Would you specify a separate vapor retarder material in warm climates (Climate zones 1 to 3)? Give reason(s) for your answer.
9. Explain why an attic space must be ventilated.

CHAPTER 7

Fire- and Smoke-Related Properties

CHAPTER OUTLINE

7.1 Factors That Affect Fire and Smoke Safety in Buildings
7.2 Fire Code and Building Code
7.3 Combustible and Noncombustible Materials
7.4 Products Given off in a Building Fire
7.5 Fire-Resistance Rating—Measure of an Assembly's Fire Endurance
7.6 Types of Construction
7.7 Determining the Type of Construction of a Building
7.8 Fire-Test Response Characteristics of Interior Finishes
7.9 Essentials of Passive Fire Protection — Compartmentalization of Building
7.10 Essentials of Passive Fire Protection — Opening Protection and Fire Sealing of Penetrations and Joints
7.11 Essentials of Active Fire Protection

Fires that could engulf an entire neighborhood or a city (such as the Great Fire of London) are rare these days. This is because of sustained improvements in fire safety and zoning regulations and advances in fire detection and suppression equipment used in buildings. Today fires are generally limited to individual buildings or a small group of buildings. If fire safety considerations were less stringent than those currently in use, fire of the severity shown in Figure 7.1 would have not only caused the total destruction and collapse of this building, but also produced a domino effect that would have burned and destroyed a large area of the city.

Despite various improvements in fire-safe design and construction, the fatalities and injuries caused by fires, and the resulting property losses are still substantial, justifying continued research into fire-safe materials and construction systems. Even though they are gradually decreasing, fire continues to be the single largest killer of building occupants in the United States. For instance, 2,855 people (excluding firefighters) died in the United States in 2013 from fires occurring in structures as compared with 263 from all natural disasters (earthquakes, hurricanes, snowstorms, and floods), Figure 7.2. This illustration also shows that one- and two-family dwellings are most vulnerable to fire, and explains why several code specialists argue in favor of equipping all one- and two-family dwellings in the United States with automatic sprinkler systems.

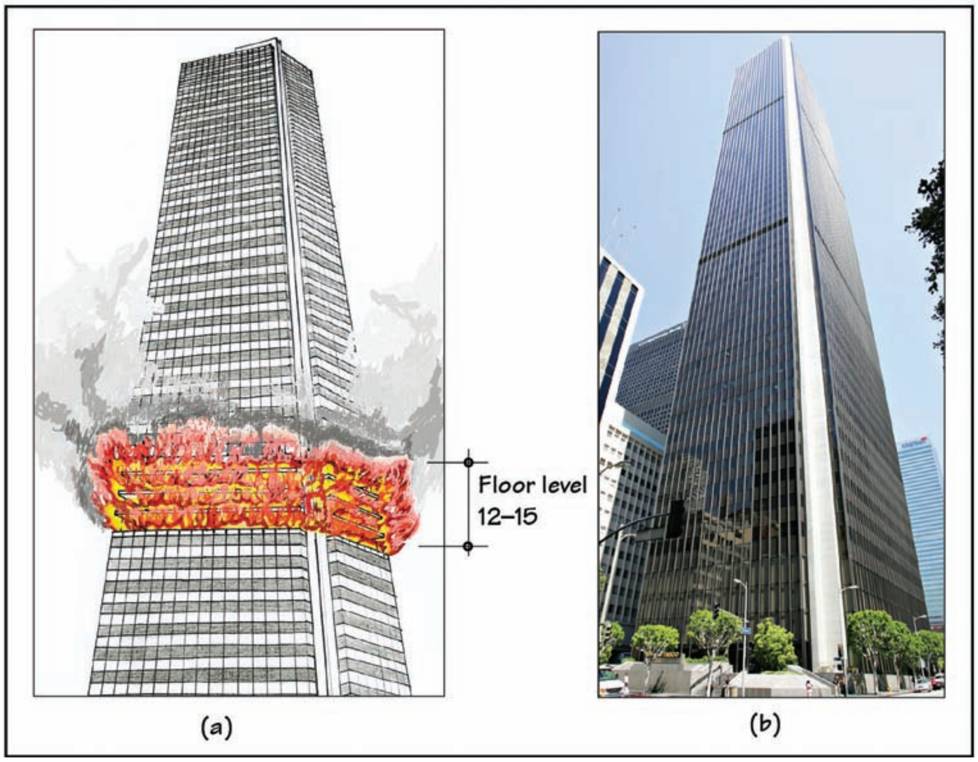


FIGURE 7.1 **(a)** Sketch of the 62-story Aon Center in Los Angeles, California, whose four floors were gutted with fire in 1988. The building is a steel frame building with spray-on fire protection on its structural members. It was not equipped with automatic sprinkler system because, in 1973 when the building was constructed, the Los Angeles Building Code did not require it. The fire, which began at about 10 PM and lasted for nearly 4 h, damaged the four floors of the building (levels 12 to 15) extensively. After substantial repairs, the building was brought back in service and is still standing, as shown in **(b)**. Its survival is ascribed to the spray-on fire protection and the heroism of the firefighters. Note that the building was called First Interstate Bank Building in 1988, and was given its present name (Aon Center) in 2003.

The sketch of the building is an extremely rough illustration of the catastrophic event. More authentic imagery and (or) details of the fire are available on the world-wide web. (Photograph by Mathias Beinling/Alamy Stock Photo)

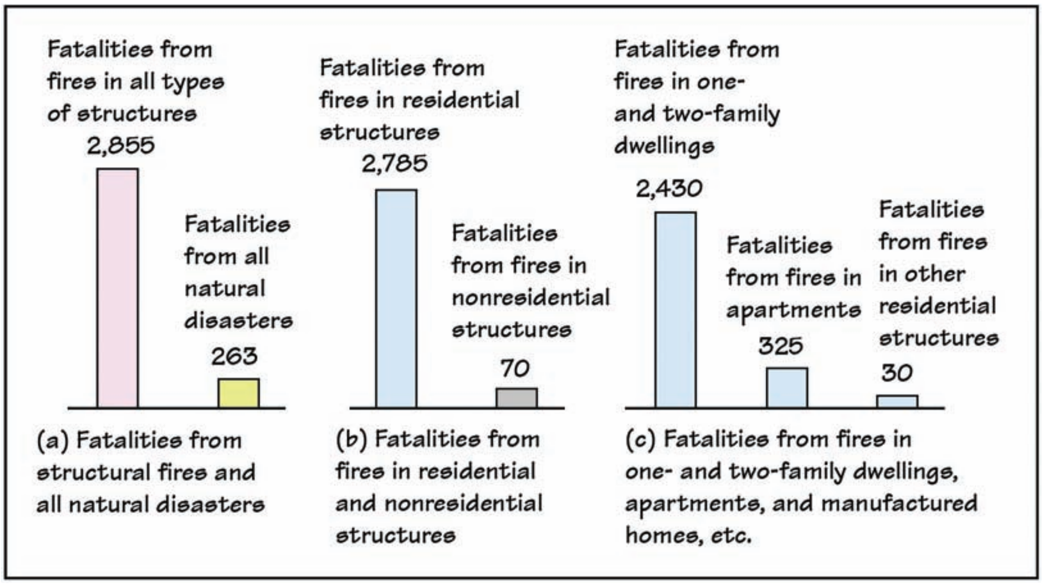


FIGURE 7.2 Statistics of civilian (excludes firefighters) fatalities from fires in residential and nonresidential structures in United States as compared with those from all natural disasters (thunderstorms, snowstorms, earthquakes, and flash floods) in 2013. Note that most fatalities due to fires occur in one- and two-family dwellings [Refs. 7.1 and 7.2]. Although this statistic is for 2013, it is typical of most recent years.

FIRE AND SMOKE SAFETY—AN IMPORTANT FOCUS OF BUILDING CODES

Because fire is the biggest hazard to life safety in modern buildings, building codes recognize this fact by making fire protection an important objective. For example, the classification of buildings in various occupancy groups, as provided in building codes, is based primarily on the degree of fire hazard present in buildings. The maximum permissible building area and height are also based on the ability of various construction assemblies to withstand fire. In fact, if the structural engineering provisions are disregarded in a building code, then nearly two-thirds of the remaining regulations relate (directly or indirectly) to fire- and smoke-safety considerations.

7.1 FACTORS THAT AFFECT FIRE AND SMOKE SAFETY IN BUILDINGS

Fire safety in buildings is a function of several variables, which may be grouped under the following three categories: (a) architectural design, (b) fire protection systems, and (c) public education, Figure 7.3. Fire-safe architectural design, an extensive area of study in itself, is outside the scope of this text. Briefly, it relates to the design features of a building that reduce the fire hazard and assist in *speedy evacuation* of people in the event of a fire.

Fire protection of a building is of two types—*active fire protection* and *passive fire protection*. Active fire protection relates to extinguishing or suppressing the fire after it occurs by using automatic sprinklers. In addition to sprinklers, the active protection system includes fire detection, alarm system, hydrants, standpipes, and other firefighting equipment.

Passive fire protection is an integral part of the building's materials and construction, whose purpose is to increase the fire endurance of building assemblies, contain ignition, and retard the spread of fire. Note that both active and passive protection systems are equally important. However, because the passive protection is integral with building components, it has direct impact on fire- and smoke-related properties of assemblies.

On the other hand, the active protection system is a part of the mechanical services in buildings. Therefore, it impacts fire- and smoke-related properties of assemblies indirectly—in situations where the building codes allow reduction in the degree of passive protection if active protection system is provided. Therefore, in this chapter, only a brief account of active protection system is provided—to primarily highlight its relationship with passive protection.

7.2 FIRE CODE AND BUILDING CODE

In addition to the building code, a building is regulated by the jurisdiction's fire code. As previously stated, fire safety is one of the prime objectives of a building code. However, once the building has been constructed and occupied, it must be properly maintained to remain safe against fire and other hazards. The regulations that cover aspects of fire safety in a building during its use and occupancy are included in the *fire prevention code*, or simply the *fire code*.

The fire code regulates such items as the location of fire protection appliances; installation, periodic inspection, and maintenance of active protection system; maintenance of the means of egress so that it remains unblocked at all times; the storage of combustible and (or) hazardous materials; and so on. For example, the storage of flammable liquids in a dry cleaning establishment is regulated by the fire code, but the construction of the enclosure to store the flammable liquids and the requirement for an automatic fire suppression system are contained within the building code. While the jurisdiction's building official is responsible for the enforcement of the building code, the fire code is enforced by the jurisdiction's *fire official*.

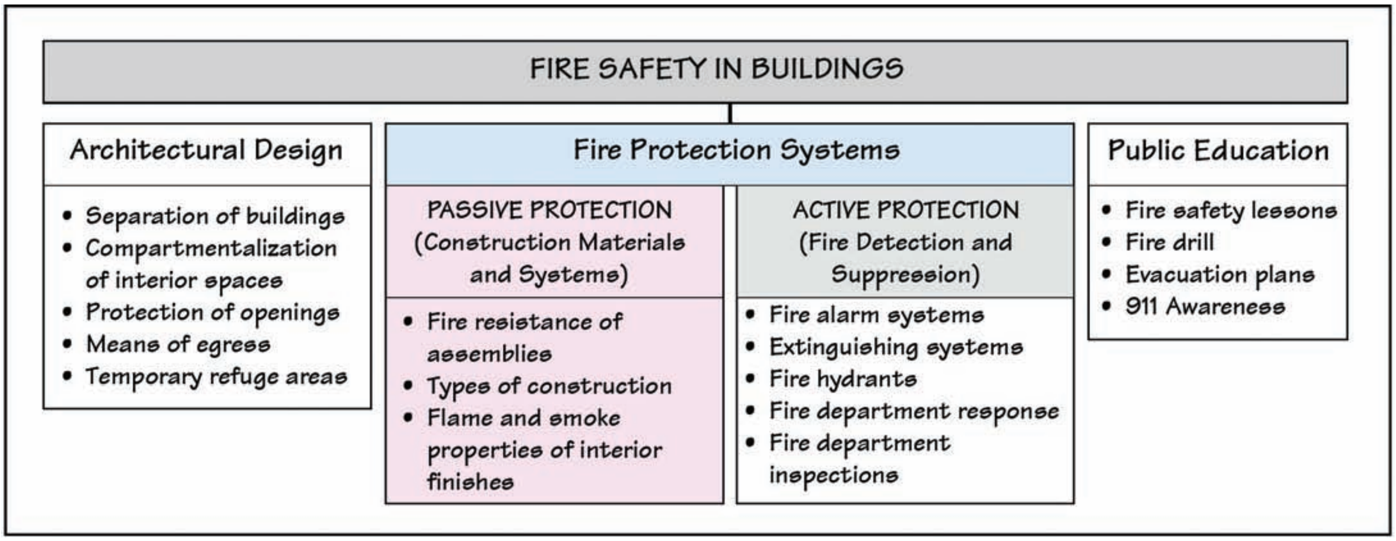
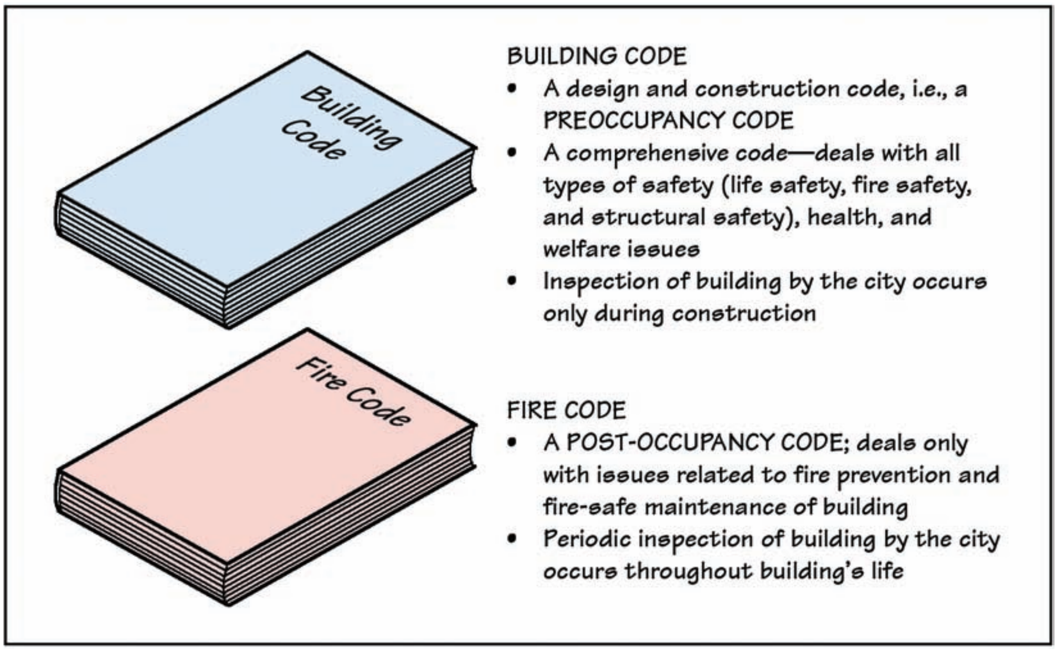

FIRE SAFETY IN BUILDINGS
Architectural Design
• Separation of buildings
• Compartmentalization of interior spaces
• Protection of openings
• Means of egress
• Temporary refuge areas
Fire Protection Systems
PASSIVE PROTECTION (Construction Materials and Systems)
• Fire resistance of assemblies
• Types of construction
• Flame and smoke properties of interior finishes
ACTIVE PROTECTION (Fire Detection and Suppression)
• Fire alarm systems
• Extinguishing systems
• Fire hydrants
• Fire department response
• Fire department inspections
Public Education
• Fire safety lessons
• Fire drill
• Evacuation plans
• 911 Awareness

FIGURE 7.3 Factors that affect fire safety in buildings. In this chapter, we will focus mainly only on passive fire protection systems.



BUILDING CODE

- A design and construction code, i.e., a PREOCCUPANCY CODE
- A comprehensive code—deals with all types of safety (life safety, fire safety, and structural safety), health, and welfare issues
- Inspection of building by the city occurs only during construction

FIRE CODE

- A POST-OCCUPANCY CODE; deals only with issues related to fire prevention and fire-safe maintenance of building
- Periodic inspection of building by the city occurs throughout building's life

FIGURE 7.4 Important differences between building code and fire code.

While both codes must be referenced during the design and construction of buildings, the role of building code ends after the building is occupied. Therefore, the building code may be seen as *pre-occupancy code*. The role of fire code during the design and construction stages is relatively small, but because the building is frequently inspected by the fire official's office to ensure its fire-safe maintenance, the fire code may be seen as *post-occupancy code*, Figure 7.4.

Fire-safe maintenance is possible only if the building is equipped with fire-safety features. Therefore, there are several overlapping provisions in the fire code and the building code, and the fire official's office and the building official's office work in close cooperation because the aims of both are the same—to ensure public safety.

7.3 COMBUSTIBLE AND NONCOMBUSTIBLE MATERIALS

In the context of fire-safe construction, building materials must be distinguished either as *combustible materials* or as *noncombustible materials*. Metals used in construction (iron, steel, aluminum, copper, etc.) and concrete, brick, stone, gypsum, and so on, are noncombustible materials. Wood, paper, and plastics are combustible materials.

The distinction between a combustible and a noncombustible material is generally, but not always, obvious. For example, steel and aluminum are noncombustible materials, but steel dust and aluminum dust are combustible. Also, it is not immediately clear whether fire-retardant-treated (FRT) wood is a combustible or a noncombustible material. Additionally, some materials may contain a small combustible content, which may or may not contribute appreciably to a fire, such as concrete made with polystyrene beads as aggregate. Are these materials to be considered combustible or noncombustible materials?

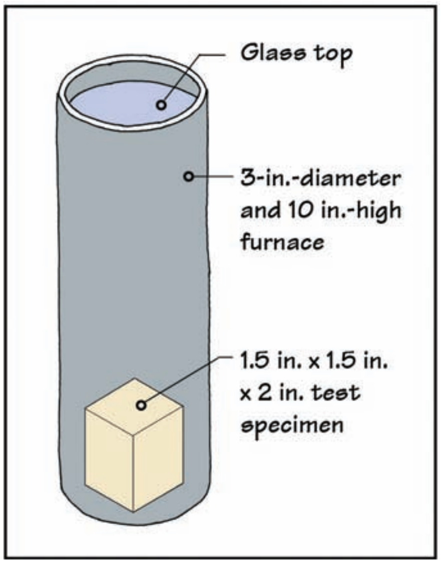

Glass top
3-in.-diameter and 10 in.-high furnace
1.5 in. x 1.5 in. x 2 in. test specimen

FIGURE 7.5 ASTM E136 test setup to determine whether a material is combustible or noncombustible.

A precise definition of noncombustibility is, therefore, necessary. A noncombustible material is defined as a material that will not propagate fire, that is, *neither ignite nor burn when subjected to: (a) heat or (b) fire*. Noncombustibility is determined through ASTM E136 Test. In this test, a predried specimen of the material measuring $1\frac{1}{2}$ in. × $1\frac{1}{2}$ in. × 2 in. is placed in a 3-in.-diameter cylindrical furnace, Figure 7.5. Before the material is placed in the furnace, the furnace temperature is raised to 1,382°F (750°C). The furnace has a transparent lid to allow the inspection of the specimen during the test. The specimen is reported as noncombustible if it satisfies the conditions laid down in the test.

FIRE-RETARDANT-TREATED (FRT) WOOD OR FRT PLYWOOD AS COMBUSTIBLE MATERIALS

Fire-retardant-treated (FRT) lumber and plywood do not pass the ASTM E136 test and are, therefore, classified as combustible materials. However, recognizing that FRT wood makes a reduced contribution as fuel in the early stages of fire, building codes permit its use in some limited situations where only noncombustible materials are allowed.

For example, non-load-bearing partitions in Type I and Type II construction, which are otherwise required to be of noncombustible materials (metal stud and gypsum board assemblies), may be constructed of FRT wood framing. Similarly in Types III and IV construction, in which the exterior walls must be of noncombustible materials, FRT wood is allowed as a substitute for noncombustible materials—masonry, steel, or concrete. (See Section 7.6 for the types of construction.)

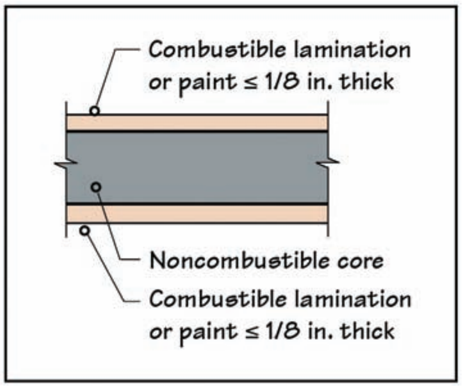


FIGURE 7.6 A material with a noncombustible core but with a combustible lamination less than or equal to $\frac{1}{8}$ in. (3 mm) thickness is regarded by the building codes as a noncombustible material.

APPLICABILITY OF ASTM E136 TEST

ASTM E136 test is applicable only to elementary materials, not to composites, laminated, or coated materials. In recognition of the fact that a material with a noncombustible core (as per the ASTM E136 test), but with a thin facing of a combustible material or a combustible paint, does not contribute greatly to fire, building codes classify such a material as a noncombustible material, Figure 7.6.

The constraints placed on the combustible paint or laminate are that its thickness shall not exceed $\frac{1}{8}$ in. and its flame spread index shall not exceed 50 (see Section 7.8 for the explanation of flame spread index). Thus, gypsum board, which has a thin paper lining, is classified as a noncombustible material because the thickness of the combustible paper lining is less than $\frac{1}{8}$ in.

NONCOMBUSTIBILITY OF A MATERIAL AND ITS ABILITY TO WITHSTAND FIRE

Note that noncombustibility refers only to the fact that a noncombustible material will not add fuel to the fire. Noncombustibility is not related to the ability of the material to withstand fire. For example, wood is a combustible material and steel is a noncombustible material, but a structure constructed of heavy sections of wood is better able to withstand fire than one constructed of unprotected steel members, as explained later in this chapter.

7.4 PRODUCTS GIVEN OFF IN A BUILDING FIRE

The two products given off in a building fire (referred to as *products of combustion*) are heat and smoke. Smoke consists of: (a) fire gases, (b) solid particulate matter (fine particles of solid matter suspended in the atmosphere), and (c) liquid particulate matter (condensed vapors dispersed in the atmosphere as tiny liquid droplets), Figure 7.7. Although fire gases in smoke are generally transparent, the solid and liquid particulate matter form an opaque cloud and diminish visibility in a fire.

Both products of combustion—smoke and heat—are responsible for human deaths and injuries. The statistics based on autopsies conducted on people who died in building fires indicate that, because of smoke's toxicity, smoke inhalation accounts for nearly 65% of all deaths. Burns and heat account for 30%, and the remaining 5% of deaths are caused by emotional shock and heart failure, Figure 7.8.

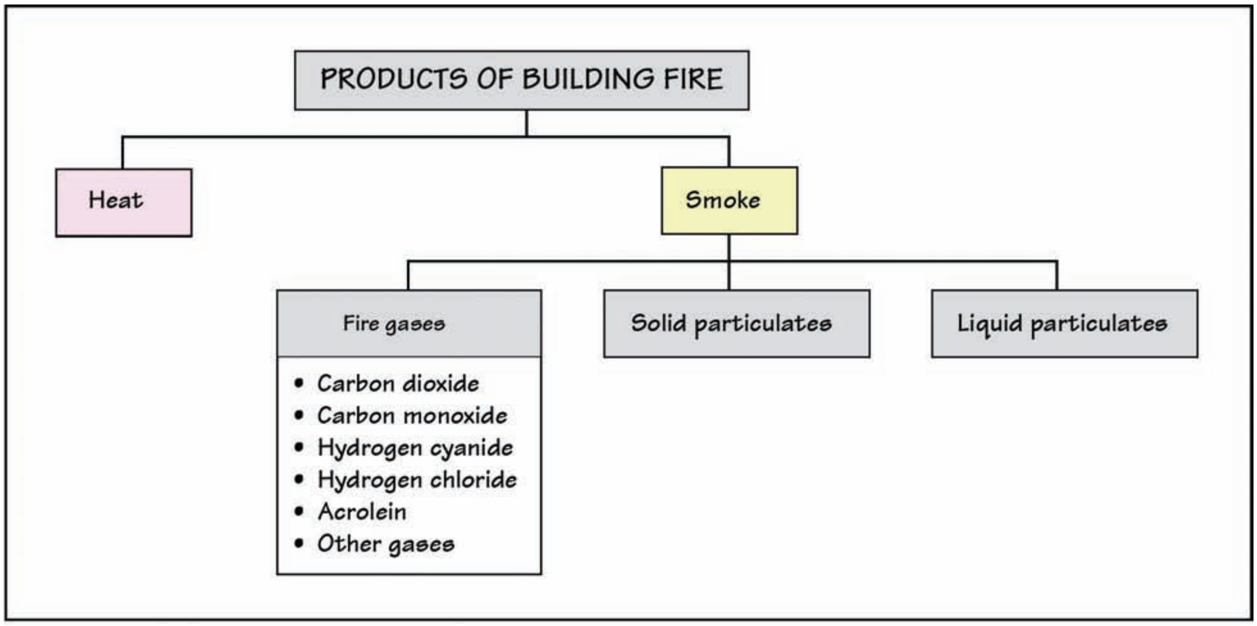


FIGURE 7.7 Products of combustion in a building fire.

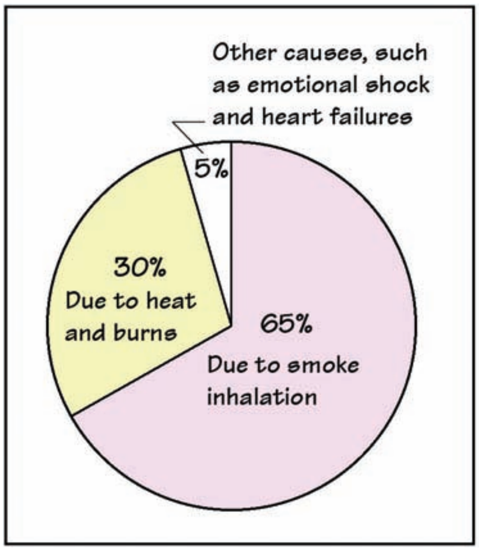


FIGURE 7.8 Causes of deaths in a building fire.

The toxicity of smoke is due to gases produced in a fire. The types of gases depend on the type of material that burns. Carbon dioxide and carbon monoxide are produced in almost all fires. If a sufficient supply of oxygen (air) is available during the fire, the carbon that is present in almost every combustible material, such as wood, cotton, silk, wool, and plastics, is converted to carbon dioxide (CO_2). This type of combustion is called *complete combustion*. However, most fires take place under conditions of incomplete combustion, where the amount of oxygen available is less than that required for complete combustion. In such a case, carbon monoxide (CO) is produced.

Both carbon dioxide and carbon monoxide are toxic to humans. However, carbon monoxide is considered the major threat to human life in building fires. Although less toxic than some of the other fire gases, it is generally present in such large quantities that its overall toxic effect is most devastating. It is estimated that nearly 50% of fatalities caused by smoke inhalation occur due to the effect of carbon monoxide.

Carbon dioxide is also present in large quantities in a building fire, but its toxicity is considerably lower than that of carbon monoxide. Other gases produced in a fire may include hydrogen cyanide, hydrogen chloride, or acrolein. Hydrogen cyanide is produced from the burning of wool, silk, leather, rayon, and plastics containing nitrogen. Hydrogen chloride is produced from polyvinyl chloride (PVC). Acrolein is produced from wood and paper.

EFFECT OF SMOKE ON VISIBILITY

The solid and liquid particulate matter in smoke reduces visibility. Although reduced visibility has no direct effect on fire fatalities, it impedes the escape of a building's occupants and prolongs their exposure to toxic gases and heat. This often results in panic conditions, which are known to have caused several deaths in building fires. Smoke also has irritating effects on eyes and lungs, and this may result in serious medical problems.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. Based on the statistics of fatalities in building fires in the United States, which building type has the worst record?
- **a.** Office buildings
- **b.** Hotel buildings
- **c.** Industrial buildings
- **d.** Multifamily dwellings
- **e.** One- and two-family dwellings

2. The design of the means-of-egress system in a building is a part of
- **a.** active fire protection.
- **b.** passive fire protection.
- **c.** basic fire protection.
- **d.** upgraded fire protection.
- **e.** none of the above.

3. The automatic sprinkler system in a building is a part of
- **a.** active fire protection.
- **b.** passive fire protection.
- **c.** basic fire protection
- **d.** upgraded fire protection
- **e.** none of the above.

4. Fire detection system in a building is a part of
- **a.** active fire protection.
- **b.** passive fire protection.
- **c.** basic fire protection.
- **d.** upgraded fire protection.
- **e.** none of the above.

5. The fire code is one of the most important chapters in a building code.
- **a.** True
- **b.** False

6. A material whose core is noncombustible but is covered with a combustible lamination or paint is considered a noncombustible material, provided that the thickness of the paint or lamination does not exceed
- **a.** 1 in.
- **b.** $\frac{1}{2}$ in.
- **c.** $\frac{1}{4}$ in.
- **d.** $\frac{1}{8}$ in.
- **e.** $\frac{1}{16}$ in.

7. Statistics based on autopsies conducted on people who died in building fires indicate that most deaths occur due to
- **a.** burns.
- **b.** smoke.
- **c.** emotional shock.
- **d.** heart failure.

8. Based on ASTM E136 test, fire-retardant-treated (FRT) wood is a
- **a.** noncombustible material.
- **b.** combustible material and hence it cannot be used in assemblies where the use of noncombustible materials is mandated.
- **c.** combustible/noncombustible material and hence it can be used in assemblies where the use of noncombustible materials is mandated.
- **d.** combustible material but is allowed to be used in several assemblies where the use of noncombustible materials is mandated.
- **e.** none of the above.

7.5 FIRE-RESISTANCE RATING—MEASURE OF AN ASSEMBLY'S FIRE ENDURANCE

The passive fire protection of a building depends primarily on the fire endurance of building assemblies. The longer an assembly endures fire, the greater the level of passive protection it provides. Note that all building assemblies, regardless of their material, will eventually crack, disintegrate, collapse, burn, or melt in a building fire of sufficient intensity and duration. In other words, building assemblies endure fire for a limited duration, giving time to occupants to escape to safety until exterior and (or) interior firefighting measures come into action.

The ability of an assembly to endure fire is called the *fire-resistance rating* or simply the *fire rating* of the assembly. It is measured in units of time, that is, in hours or fractions thereof. Thus, a 1-h fire rating means that the assembly can endure a typical building fire for at least 1 h; a 2-h fire rating means that it can endure fire for at least 2 h. Similarly, a 20-min fire rating implies a minimum fire endurance of 20 min.

FIRE RATING—A PROPERTY OF THE ASSEMBLY, NOT THE MATERIAL

Note that by virtue of its definition, the fire rating is a property of the assemblies, such as walls, floors, and roofs, and not simply of the materials of which the assemblies are constructed. Thus, the fire rating of a single material, such as concrete or wood, is meaningless. Therefore, in specifying the fire rating of an assembly, all its details must be given including the specifications and thickness of each component, types of fasteners, their spacing, air space between components (if any), and so on.

DETERMINATION OF FIRE RATING

There are two procedures to determine the fire rating of a building assembly: (a) through calculations and (b) through tests conducted on the specimen of the assembly in a furnace. The calculation procedure at the present time has not sufficiently advanced and has limited applications. Therefore, the fire rating of an assembly is obtained from tests conducted in an independent testing laboratory according to ASTM Standard E119 "Standard Test Methods for Fire Tests of Building Construction and Materials".

The most commonly used laboratory for fire tests in North America is the Underwriters Laboratories Inc. (UL). The laboratory receives full-size (i.e., unscaled) test specimens from the manufacturer whose workmanship and construction details must be representative of the actual assembly used in the building. The minimum dimensions of the specimen assembly are prescribed by the standard.

The specimen is placed against the opening of the test furnace and the joints between the opening and the specimen are sealed before starting fire in the furnace. The rise in furnace temperature is controlled according to the standard time-temperature relationship, which represents the rise of temperature in an intense, full-blown building fire. Two types

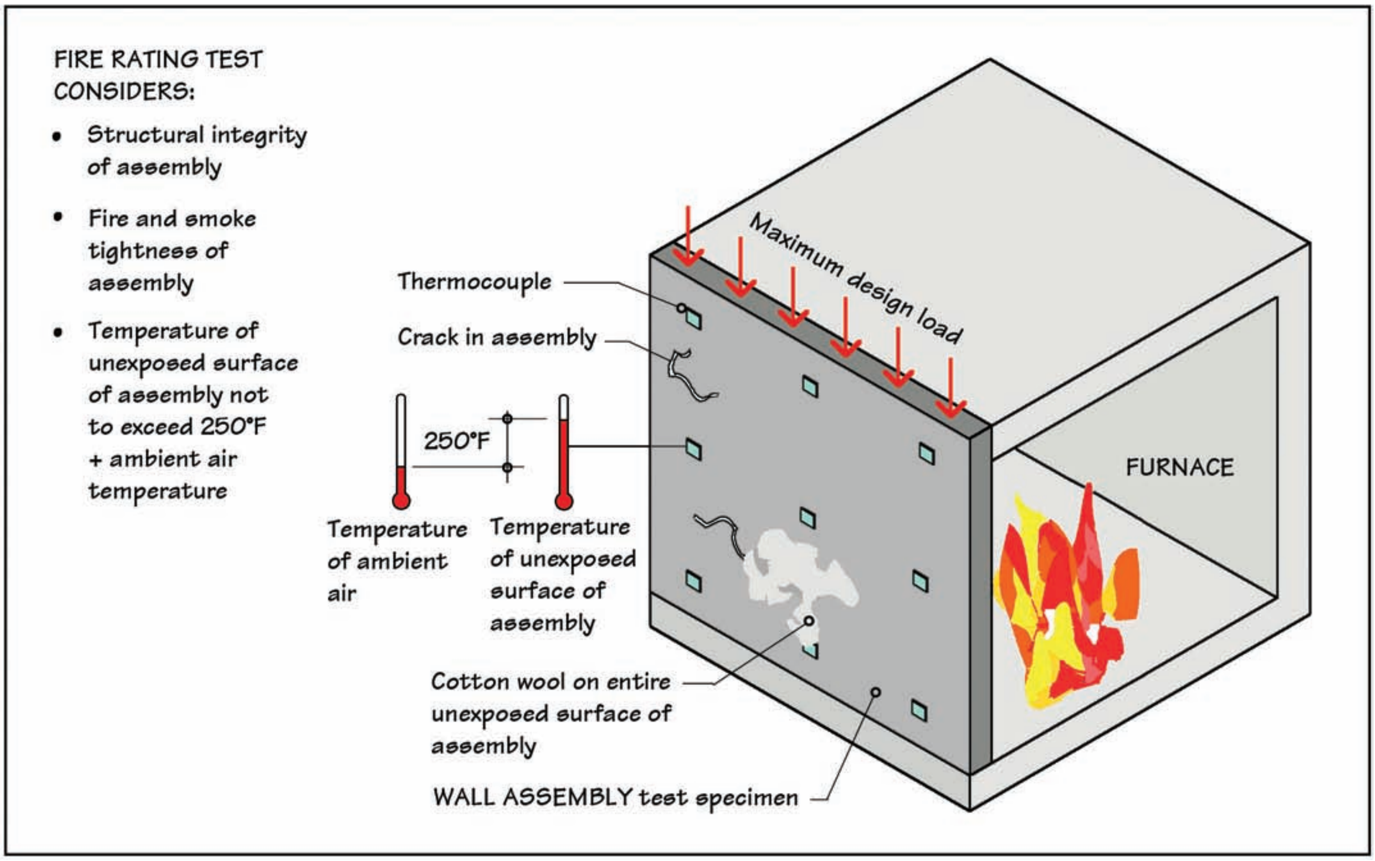

FIRE RATING TEST CONSIDERS:
• Structural integrity of assembly
• Fire and smoke tightness of assembly
• Temperature of unexposed surface of assembly not to exceed 250°F + ambient air temperature
Maximum design load
Thermocouple
Crack in assembly
250°F
Temperature of ambient air
Temperature of unexposed surface of assembly
Cotton wool on entire unexposed surface of assembly
WALL ASSEMBLY test specimen
FURNACE

FIGURE 7.9 Setup for measuring the fire rating of a wall assembly according to ASTM E119 standard. For a vertical assembly (wall or column), a vertical furnace is used, as shown here. For a horizontal assembly (beam, truss, floor, or roof), a horizontal furnace is used.

NOTE

Fire-Rating Data from Manufacturers' Publications and Building Codes

The fire ratings of assemblies tested by the Underwriters Laboratories are given in its annual publication, entitled the *UL Fire Resistance Directory*, which is the most comprehensive source available for fire ratings of assemblies, and is available in hardcopy and digital formats. Additionally, building codes provide tables, listing the fire ratings of a number of commonly used assemblies.

Other commonly referenced sources are publications by the manufacturers' associations. For example, *Fire Resistance Design Manual* published by Gypsum Association (an association of gypsum board manufacturers) is an authoritative source for the fire-resistance ratings of assemblies using gypsum board. Similarly, the fire-resistance ratings of concrete masonry walls are usually obtained from the publication of National Concrete Masonry Association (NCMA).

of furnaces are used, one for vertical assemblies, as shown in Figure 7.9, and the other for horizontal assemblies. Vertical furnace is used for walls and columns, and the horizontal furnace is used for roofs, floors, beams, and trusses.

Because fire rating is a measure of the fire endurance of the assembly, whose purpose is to provide safety against fire and smoke, the fire test evaluates the following three attributes of the assembly.

1. **Structural Integrity:** A fire-rated assembly should be able to perform its structural function without collapse, that is, it should be able to sustain the loads for which it has been designed. Therefore, the specimen is subjected to the maximum design load throughout the duration of the test.
2. **Fire and Smoke Tightness:** A fire-rated assembly should remain fire-tight; that is, it should develop no cracks during the duration of the fire. The purpose of this requirement is to ensure that smoke and flames will not spread to adjacent compartments. The fire and smoke tightness is evaluated by placing cotton wool on the entire unexposed face of the assembly, as shown in Figure 7.9. In a cracked assembly, the cotton wool will burn.
3. **Low Temperature of Unexposed Face:** The temperature of the unexposed face of a fire-rated assembly during a fire should be so low that the heat received by radiation and (or) conduction from the assembly will not ignite combustibles in adjacent compartments. The standard requires that the average temperature of the unexposed face of the assembly should not rise more than 250°F above the ambient air temperature. Therefore, a number of thermocouples are attached to the unexposed face of the assembly to monitor its surface temperature.

As soon as any one of these three attributes is violated, the test is stopped and the test duration determines the assembly's fire rating.

7.6 TYPES OF CONSTRUCTION

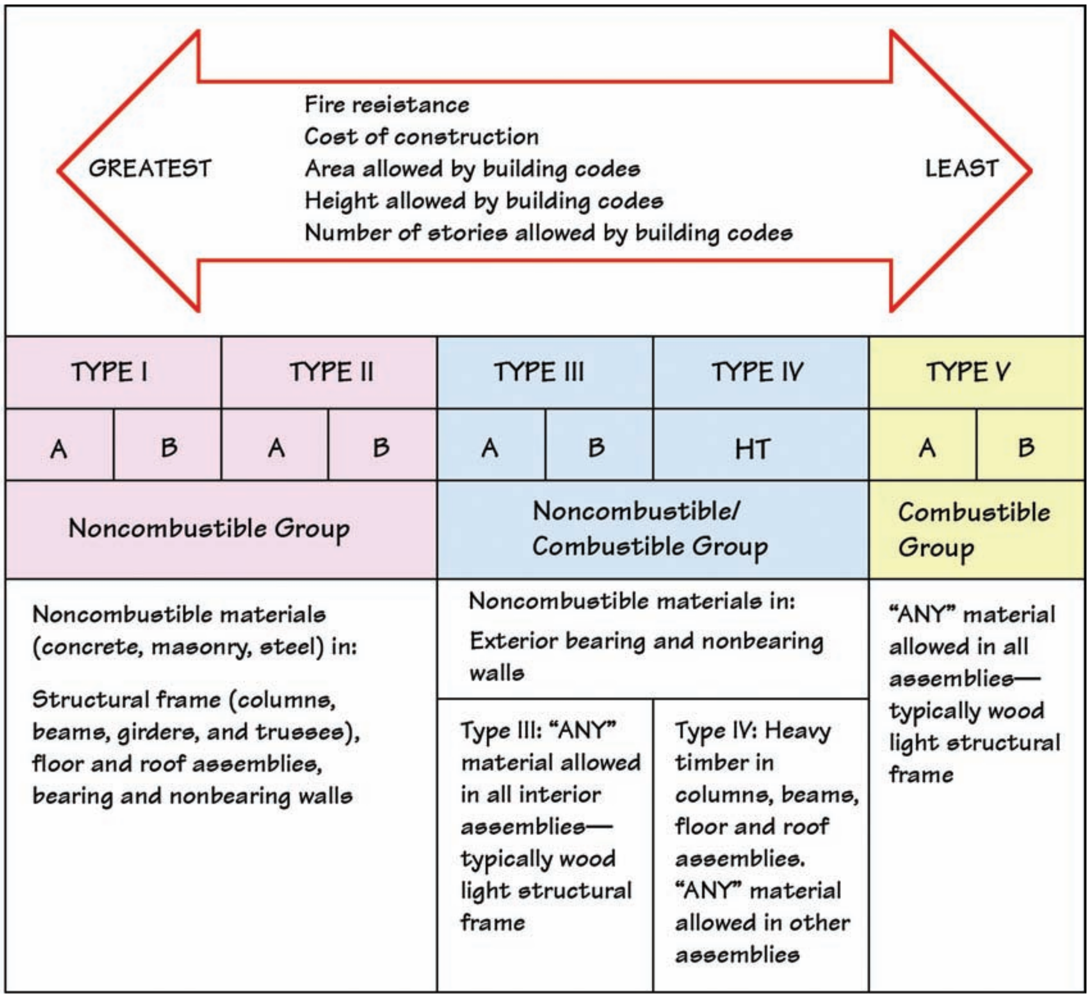
As stated in Chapter 2, the type of construction classification of a building, as given in the building codes, falls into the following five categories:

- Type I
- Type II
- Type III
- Type IV
- Type V

Type I construction is the most fire resistive, and Type V construction is the least fire resistive. For a given occupancy, building codes allow greater area, greater height, and greater number of stories for a more fire-resistive type of construction (see Chapter 2, Principles in Practice). A more fire-resistive construction is also more costly (per sq ft).

Types I, II, III, and V are further divided into subtypes A and B. Thus, there are, in fact, nine types of construction classifications—Type I(A), Type I(B), Type II(A), and so on. Based on the type of materials used in them, the nine types of construction are grouped in three groups described here, and illustrated in Figure 7.10.

- *Noncombustible Group*—consists of Type I and Type II: In these types of construction, all load-bearing assemblies (columns, beams, floors, roofs, and walls), and non-load-bearing walls must be of noncombustible materials (concrete, masonry, or steel).
- *Noncombustible/combustible Group*—consists of Type III and Type IV: In these types of construction, the exterior walls must be of noncombustible materials, whereas other assemblies may be of any material (combustible or noncombustible). The practical implication of the term "any material" is the use of wood because of its lower cost in comparison with noncombustible materials. Fire-retardant-treated lumber is allowed to be used in exterior wall assemblies of this group, and is recognized as equivalent to a noncombustible material (see Section 7.3). Therefore, for all practical purposes, the structural members of Types III and IV are of wood with exterior walls of masonry, concrete, steel, or fire-retardant-treated wood frame.
- *Combustible Group*—consists of Type V: In this group, all envelope and structural elements may be of any material (combustible or noncombustible).


GREATEST
Fire resistance
Cost of construction
Area allowed by building codes
Height allowed by building codes
Number of stories allowed by building codes
LEAST

TYPE I		TYPE II		TYPE III		TYPE IV	TYPE V	
A	B	A	B	A	B	HT	A	B
Noncombustible Group				Noncombustible/ Combustible Group			Combustible Group	
Noncombustible materials (concrete, masonry, steel) in: Structural frame (columns, beams, girders, and trusses), floor and roof assemblies, bearing and nonbearing walls				Noncombustible materials in: Exterior bearing and nonbearing walls			"ANY" material allowed in all assemblies—typically wood light structural frame	
				Type III: "ANY" material allowed in all interior assemblies—typically wood light structural frame		Type IV: Heavy timber in columns, beams, floor and roof assemblies. "ANY" material allowed in other assemblies		

FIGURE 7.10 Significant differences and similarities between various types of construction. For additional details, refer to the International Building Code.

FIRE RATINGS OF STRUCTURAL ASSEMBLIES AS DETERMINANTS OF THE TYPE OF CONSTRUCTION

Figure 7.11 shows the details of the classification of the nine types of construction. The classification is based on the minimum required fire ratings of the structural assemblies of the building. They include assemblies that resist the gravity loads (dead loads, live loads, rain load, snow loads, etc.) and also those that resist the lateral loads (wind and earthquake). In other words, the fire ratings of structural frame (columns, beams, girders, trusses, lateral bracing, and shear walls), floor and roof decks (slabs), and load-bearing walls, determine the type of construction of the building. (See Glossary of Terms and Index at the end of the text for description of lateral bracing and shear walls.)

The fire ratings of non-load-bearing assemblies, such as interior and exterior nonbearing walls, doors, windows, and so on, do not factor into the determination of a building's type of construction. However, it is important to repeat that the use of noncombustible materials in exterior walls (bearing or nonbearing) is mandated for Types III and IV.

The higher the fire rating of structural assemblies is, the more fire resistive is the type of construction. As shown in Figure 7.11, the building codes require these assemblies to be rated as 0, 1, 1.5, 2, or 3 h. Number 0 implies that there is no requirement for a fire rating; that is, the assembly may be a *nonrated assembly*. Because a rated assembly in Figure 7.11 must have a minimum rating of 1 h, an assembly with a rating of 59 min or less is considered a nonrated assembly, that is, with a fire rating of zero. The maximum fire rating required of any assembly for the type of construction classification is 3 h.

TYPE V(A) AND TYPE V(B) CONSTRUCTION

The least fire-resistive construction is Type V(B), in which all structural assemblies can be of combustible materials, and they need not have any fire rating. Generally, Type V(B) construction consists of wood light-frame assemblies, Figure 7.12. If this framing is covered with $\frac{1}{2}$-in.-thick Type R gypsum board on both sides, it gives the assemblies a fire rating of approximately 40 min. Because the fire rating is less than 1 h, the assemblies are considered nonrated (zero rating). Most single-family dwellings are of Type V(B) construction.

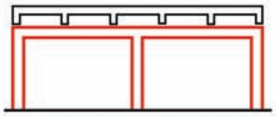
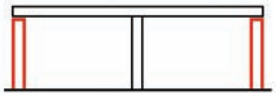
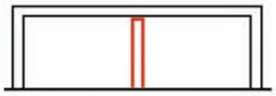
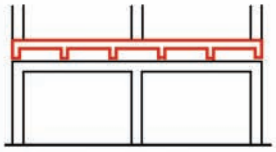
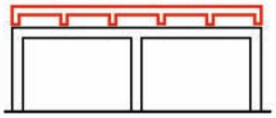
Building Element (Structural Assembly)	Minimum Fire Rating Requirements of Structural Assemblies (in Hours)								
	Noncombustible Group				Noncombustible/ Combustible Group			Combustible Group	
	Type I		Type II		Type III		Type IV	Type V	
	A	B	A	B	A	B	HT	A	B
 STRUCTURAL FRAME (columns, girders and trusses) [Note 1]	■■■ 3 h	■■ 2 h	■ 1 h	0 h	■ 1 h	0 h	HT	■ 1 h	0 h
 BEARING WALLS (Exterior) [Note 1, 2]	■■■ 3 h	■■ 2 h	■ 1 h	0 h	■■ 2 h	■■ 2 h	■■ 2 h	■ 1 h	0 h
 BEARING WALLS (Interior) [Note 1]	■■■ 3 h	■■ 2 h	■ 1 h	0 h	■ 1 h	0 h	■ 1 h or HT	■ 1 h	0 h
 FLOOR ASSEMBLY (Slabs, beams, and joists)	■■ 2 h	■■ 2 h	■ 1 h	0 h	■ 1 h	0 h	HT	■ 1 h	0 h
 ROOF ASSEMBLY (Slabs, beams, rafters, and joists)	■▬ 1.5 h	■ 1 h	■ 1 h	0 h	■ 1 h	0 h	HT	■ 1 h	0 h

FIGURE 7.11 Type of construction classification, per International Building Code (2015) published by the International Code Council.

Note 1: Fire rating of structural frame and bearing walls may be reduced by 1 h for Type 1(A) and Type 1(B) if the building supports only a roof.

Note 2: Fire rating of exterior (bearing and nonbearing) walls is also a function of fire separation distance (FSD) as explained in Section 7.9 and shown in Figure 7.27. The code requires the larger of the two values to be used—the one based on FSD and the other based on the type of construction, as shown here.

If the framing of Figure 7.12 is covered with $\frac{5}{8}$-in.-thick Type X gypsum board on both sides, the assemblies provide a 1-h rating, and it will be a Type V(A) construction (see Section 16.5 for a discussion of Type R and Type X gypsum board).

TYPE IV (HT) CONSTRUCTION

Type IV is called *heavy timber* (HT) construction. In HT construction, floors, roofs, and the structural frame are of heavy sections of wood without any added gypsum board or similar fire protection. In other words, in HT construction, the wood members are exposed without any concealed spaces such as those that occur in a conventional wood light-frame building. For example, in a conventional wood light-frame floor, concealed spaces occur between floor joists, Figure 7.13. Similar spaces occur in conventional wood light-frame walls and attics. Such spaces are absent in HT construction.

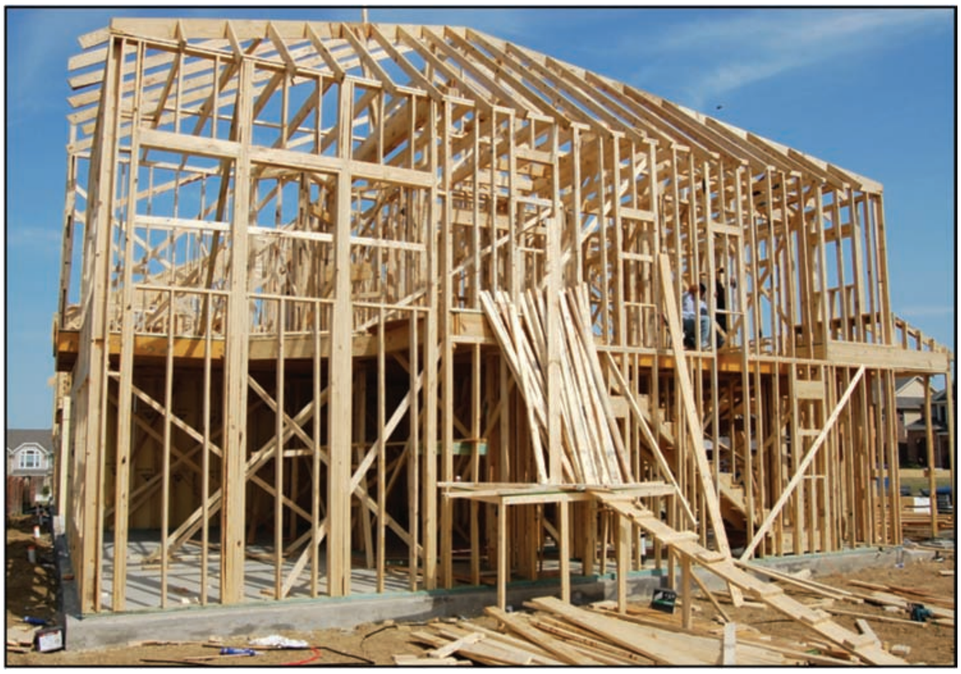


FIGURE 7.12 Most single-family dwellings in North America are constructed of wood frame construction as shown here (see also Chapters 15 and 16). The wood members are typically protected against fire with $\frac{1}{2}$-in.-thick gypsum board, which gives the wall, floor, and roof assemblies a fire rating of approximately 40 min. Because the fire rating is less than 1 h, such assemblies meet the requirements of Type V(B) construction—a nonrated construction.

HT construction is slow burning and is assumed to provide an equivalent of a 1-h fire rating. The exterior walls (load-bearing or non-load-bearing) in Type IV construction must be of noncombustible materials. An example of Type IV (HT) construction is shown in Figure 7.14.

TYPE III(A) AND TYPE III(B) CONSTRUCTION

Type III construction is similar to Type IV construction in that the exterior walls (both bearing and nonbearing) of Type III(A) and Type III(B) must also be of noncombustible materials. The other features of Type III construction are similar to Type V construction. In other words, a Type III(A) construction is similar to Type V(A) construction except that the exterior walls of Type III(A) are required to be of noncombustible materials. Type III(B) is similar to Type V(B) construction but with exterior walls of Type III(B) to be of noncombustible materials.

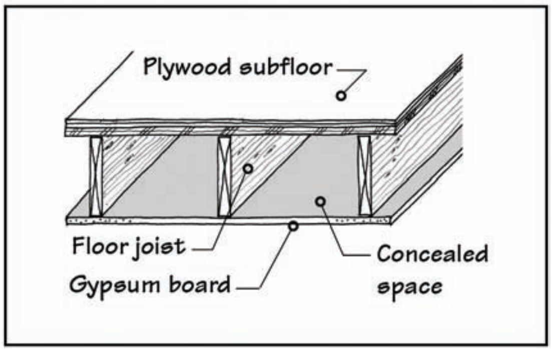


FIGURE 7.13 Floor assembly in a typical wood light-frame construction (Type V construction) illustrates concealed spaces that occur in walls, floors, and roofs of such construction.

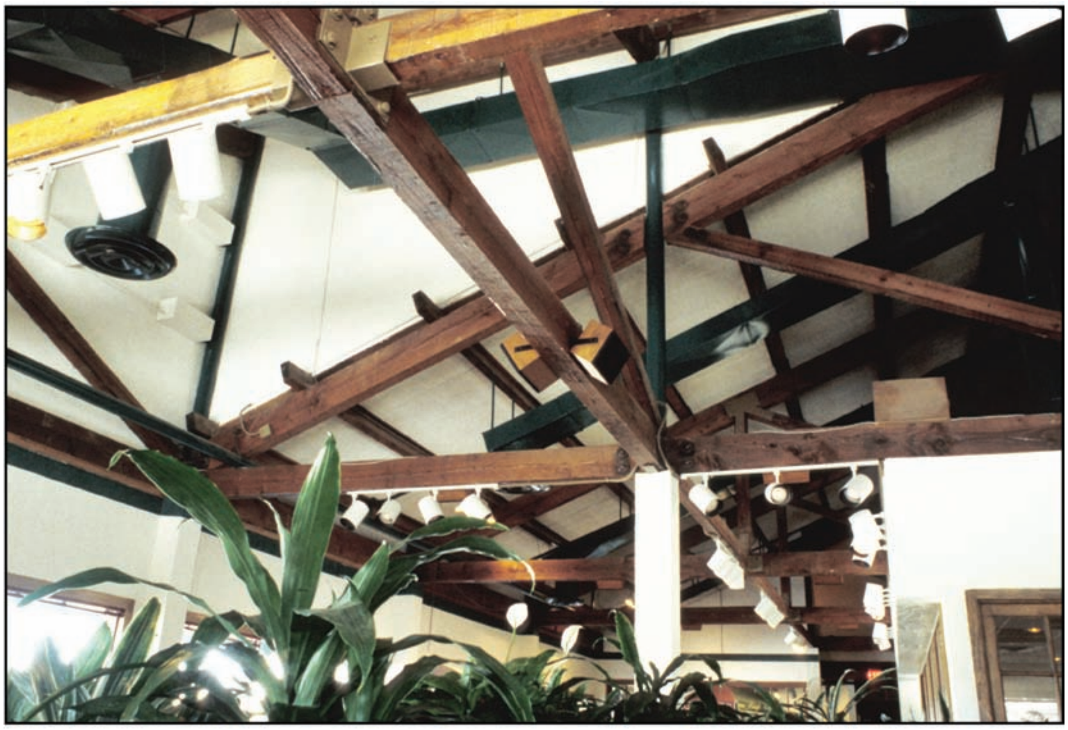


FIGURE 7.14 An example of heavy timber (HT) construction—Type IV. Notice heavy sections of wood with no protective covering and no concealed spaces.

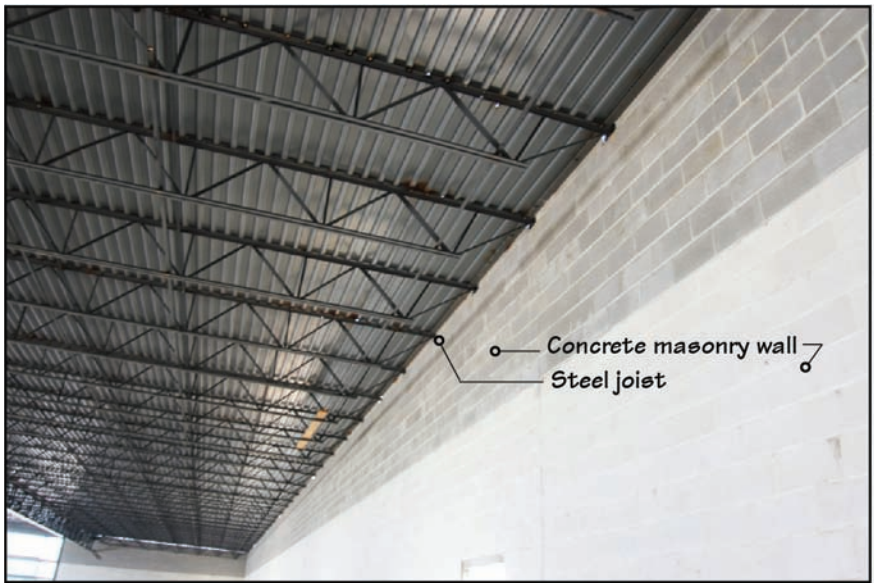

Concrete masonry wall
Steel joist

FIGURE 7.15 An example of Type II(B) construction. In this building, the load-bearing walls are of masonry, and other structural elements (columns, roof joists, and roof deck) are of steel. Therefore, it is a noncombustible type of construction—Type I or Type II. However, because the roof assembly is not protected against fire, its fire rating is (much) less than 1 h, qualifying it as a nonrated assembly. Therefore, it is a Type II(B) construction.

TYPE II(A) AND TYPE II(B) CONSTRUCTION

In terms of fire rating, Type II(A) is similar to Type III(A) because both types require the structural assemblies to have 1-h rating, see Figure 7.11. Additionally, Type II(B) is similar to Type III(B) as both require nonrated structural assemblies. The difference between them, however, is that all assemblies of Type II construction must be of noncombustible materials, while Type III can be of combustible materials except the exterior walls, which must be of noncombustible materials. With floor and roof trusses of unprotected steel, steel deck, and masonry walls, the building in Figure 7.15 is an example of Type II(B) construction. Figure 7.16 is an example of Type II(A) construction with cold-formed steel walls covered with $\frac{5}{8}$-in.-thick Type X gypsum board on both sides, and precast concrete hollow-core roof and floor slabs.

TYPE I(A) AND TYPE I(B) CONSTRUCTION

Type I(A) is the most fire-resistive construction followed by Type I(B). Generally, structural assemblies of Type I(A) and Type I(B) construction are of reinforced concrete although they can also be of structural steel. However, it is relatively easier to obtain a Type I(A) or Type I(B) classification in a reinforced concrete building as compared with a steel frame building because a steel frame building requires add-on fire protection, while a reinforced concrete building has inherent protection provided by concrete. Figure 7.17 is an example of Type I(A) construction.

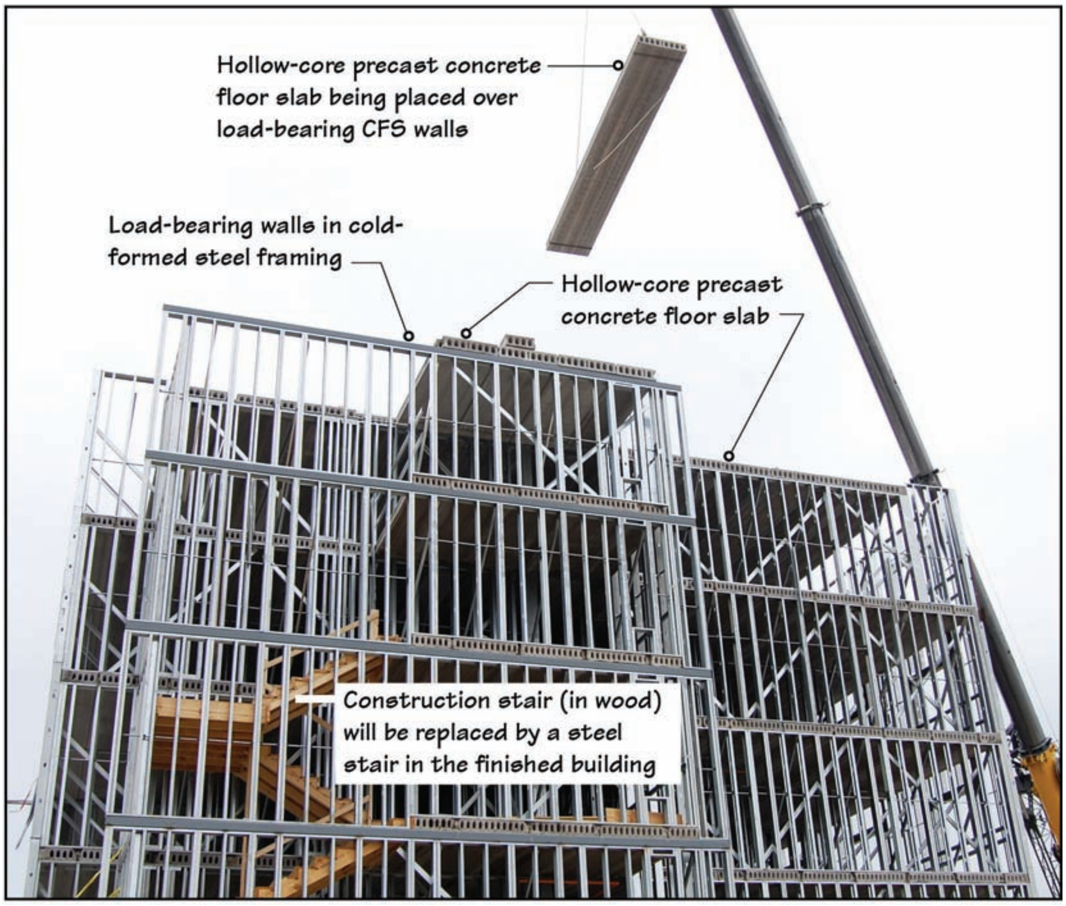

Hollow-core precast concrete floor slab being placed over load-bearing CFS walls
Load-bearing walls in cold-formed steel framing
Hollow-core precast concrete floor slab
Construction stair (in wood) will be replaced by a steel stair in the finished building

FIGURE 7.16 This hotel building (under construction) is a load-bearing wall building (no columns or beams). The walls consist of cold-formed steel (CFS) wall framing and the floors are of hollow-core precast concrete slabs. The roof will consist of prefabricated CFS trusses supported on the exterior walls. Thus, all load-bearing assemblies are of noncombustible materials, qualifying it as a Type I or Type II construction. If the walls are covered on both sides with $\frac{5}{8}$-in.-thick Type X gypsum board, and the bottom of trusses is covered similarly, the wall and roof assemblies will have a 1-h rating. The fire rating of hollow-core planks is much greater than 1-h. Therefore, the building is a Type II(A) construction.

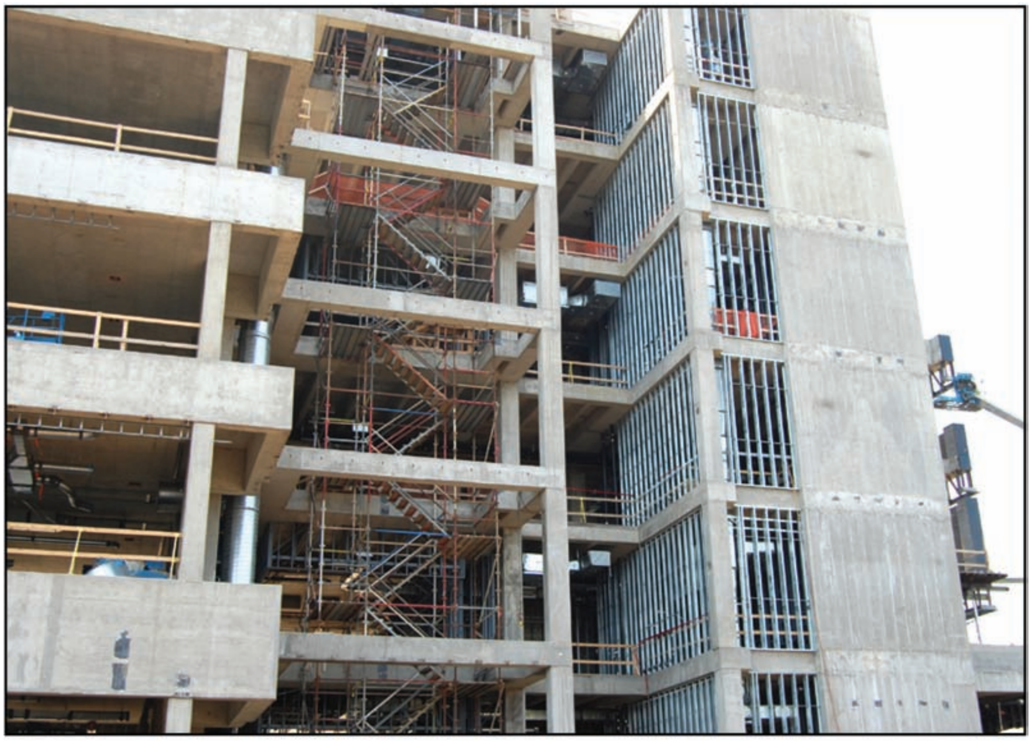


FIGURE 7.17 A cast-in-place reinforced concrete building (under construction). Such a building is generally a Type I(A) or Type I(B) construction. It is not possible to precisely judge the type without examining the construction drawings of the building because the fire rating of a cast-in-place reinforced concrete building is a function of the dimensions of the structural members and the concrete cover over steel reinforcement.

7.7 DETERMINING THE TYPE OF CONSTRUCTION OF A BUILDING

The fire ratings given in Figure 7.11 are minimum fire ratings. For a building to be classified as a given type of construction, the fire ratings of various assemblies must either equal or exceed those given in Figure 7.11. In addition to satisfying the fire-rating criterion, the building must also satisfy the criterion of combustibility or noncombustibility of materials used in structural assemblies, and in non-load-bearing interior and exterior walls. For example, if all structural assemblies are of noncombustible materials, but the interior and (or) exterior non-load-bearing walls are combustible materials, the building is classified as belonging to combustible group—Type V(A) or Type V(B) depending on the fire ratings, Figure 7.18.

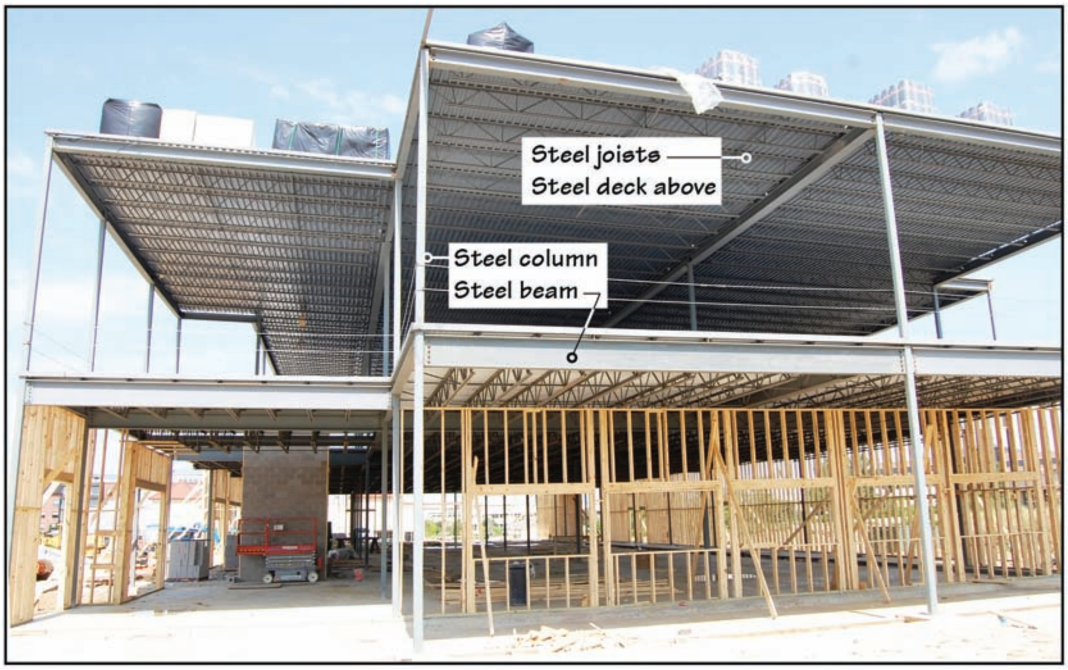


FIGURE 7.18 In this two-story office building (under construction), the structural frame (columns and beams) consists of structural steel—a noncombustible material. The floor and roof assemblies also consist of noncombustible materials (steel joists and steel deck). However, the exterior wall assemblies are of wood frame, where the wood is not fire-retardant treated (FRT). Therefore, the type of construction of this building belongs to the combustible group—Type V(A) or Type V(B). Type V(A) classification requires structural frame, and roof and floor assemblies to have a minimum 1-h rating. Because these assemblies do not have any fire protection, they are nonrated. Therefore, the building's type of construction is Type V(B). If the exterior wall framing was of cold-formed steel or FRT wood, the building would belong to the noncombustible group, and would be classified as Type II(B).

Note again that only the structural assemblies of a building determine its type of construction. In these assemblies, only the part that is structural is considered in determining whether the assembly is combustible or noncombustible. The nonstructural parts of the assembly (insulation, doors, windows, trims, etc.) are ignored because the building code allows several combustible finishes in Types I and II construction.

For example, a roof assembly consisting of a reinforced concrete slab (which is noncombustible) topped with plastic foam insulation and a polymeric roof membrane (which are both combustible) is considered a noncombustible roof assembly. Similarly, a noncombustible structural floor with a combustible floor finish, such as carpet or vinyl tiles, is regarded as a noncombustible floor.

Example 7.1

Using Figure 7.11, determine the type of construction of a building in which the materials and fire ratings of different components are as follows:

Structural frame—steel columns and steel girders	2-h
Exterior bearing walls	None provided
Interior bearing walls	None provided
Exterior nonbearing walls—cold-formed steel studs and gypsum board	0 h
Floor assemblies—steel deck on steel beams with concrete topping	1-h
Roof assembly—steel deck	1-h

Solution

Because all components are of noncombustible materials, the building is either Type I or Type II construction. Comparing the fire ratings of the building's components with those of Figure 7.11, the building is classified as Type II(A). Note that the nonbearing walls (interior or exterior) do not impact the determination of the type of construction.

Example 7.2

What changes must be made in the fire ratings of components to upgrade the construction of Example 7.1 to Type I(B)?

Solution

Examining the fire ratings required for Type I(B) construction in Figure 7.11, we see that if the fire rating of the floor assemblies of Example 7.1 is increased to a minimum of 2 h, it can be classified as Type I(B) construction.

Example 7.3

Determine the type of construction for the building in which the materials and fire ratings of different components are as follows:

Structural frame—columns, beams, and girders	None provided
Exterior bearing walls—concrete masonry	2-h
Interior bearing walls—wood studs and gypsum board	1-h
Exterior nonbearing walls—FRT wood and gypsum board	0 h
Floor assemblies—wood joists and OSB sheathing	1-h
Roof assembly—wood rafters and OSB sheathing	1-h

Solution

Because some components are of combustible materials, the building will be classified as Type III, Type IV, or Type V. Type IV is ruled out since the roofs and floors are not constructed of heavy timber. Comparing the given fire ratings with those of Figure 7.11, we observe that the building is of Type III(A) construction. Note that the exterior bearing and nonbearing walls are of noncombustible materials (or FRT wood), as required for this type of construction.

Example 7.4

If the exterior bearing walls of Example 7.3 are of wood studs and gypsum board, but with the same (2-h) fire rating, and all other components remaining unchanged, what will be the revised construction type?

Solution

Because the exterior bearing walls are of a combustible material, the type of construction will be Type V(A).

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

9. In determining the fire-resistance rating of an assembly through ASTM E119 test, which of the following properties of the assembly are investigated?
a. Structural integrity during the fire
b. Change of color of assembly during the fire
c. Occurrence of cracks in assembly during the fire
d. (a) and (b)
e. (a) and (c)

10. Fire-resistance rating is a property of
a. the material of which the assembly is made.
b. the total thickness of assembly.
c. the assembly as a whole.
d. the materials and the weight of assembly.
e. none of the above.

11. Fire-resistance rating of an assembly is measured in units of
a. time.
b. rate of temperature increase of assembly during fire test.
c. total heat released by assembly in fire test.
d. pounds per square inch.
e. none of the above.

12. Fire-resistance rating of building assemblies is generally obtained from fire tests, not through calculations.
a. True
b. False

13. Building codes divide the types of construction into
a. Types 1 to 5.
b. Types I to V.
c. Types 1 to 6.
d. Types I to VI.
e. none of the above.

14. Noncombustible types of construction are
a. Types 1, 2, and 3.
b. Types 1 and 2.
c. Types III and IV.
d. Type I.
e. Types I and II.

15. Combustible types of construction are
a. Types 4, 5, and 6.
b. Types 4 and 5.
c. Types IV, V, and VI.
d. Type VI.
e. Type V.

16. Noncombustible/combustible types of construction are
a. Types 1, 2, and 3.
b. Types 1 and 2.
c. Types III and IV.
d. Types I and II.
e. Types V and VI.

17. Among the various types of construction included in a building code, which is the most fire-resistive type?
a. Type I(A)
b. Type V(A)
c. Type V(B)
d. Type HT
e. None of the above

18. The total number of types of construction, including their subclassifications, in a building code is
a. 6.
b. 7.
c. 8.
d. 9.
e. 10.

19. In which type(s) of construction, the exterior nonbearing walls must be of noncombustible materials?
a. Type V(A)
b. Type V(B)
c. Type IV(A) and Type IV(B)
d. Type IV(C)
e. All types except Type V(A) and Type V(B)

20. Which type of construction is commonly used in a typical single-family dwelling in the United States?
a. Type V(B)
b. Type V(A)
c. Type II(B)
d. Type II(A)
e. Type IV

7.8 FIRE-TEST RESPONSE CHARACTERISTICS OF INTERIOR FINISHES

Fire-resistance rating is the property of an assembly to act as a barrier to the spread of fire to adjacent compartments. Another important fire-related property of an assembly is its ability to resist the spread of fire within the compartment of origin. This property is a function of:

- Surface burning behavior of interior finish materials
- Toxicity and density of smoke generated by the burning of finish materials

Experience with actual building fires and experimental investigations with full-scale, laboratory-based fire tests have shown that apart from providing additional fuel, interior finishes contribute to the fire hazard by (a) flaming of the material and (b) producing smoke. The properties that are used to assess these hazards are *flame-spread index* and the *smoke-developed index*, respectively.

FLAME-SPREAD INDEX (FSI)

The flame-spread index (FSI) is a measure of the rate at which flames spread on the surface of an assembly or material used as an interior finish. It is an important index because a rapid spread of flames either prevents or delays the escape of occupants from the building. Its importance was realized in the 1940s, when investigations revealed that the main cause for the loss of lives in three major building fires was the rapid spread of flames on the surfaces of interior finishes.

The FSI of a finish material is obtained from the Steiner Tunnel Test and rated on a scale that begins at zero but has no upper limit. The FSI of (select-grade) red oak has been arbitrarily fixed at 100 and that of a Portland cement board at zero. (In this respect, the FSI scale is similar to the Celsius scale, in which the boiling point of water and the freezing point of water are arbitrarily fixed at 100°C and 0°C, respectively.) Red oak has been chosen as the standard because the rate of flame travel on red oak is uniform, and the test results on red oak are reasonably reproducible.

TABLE 7.1 APPROXIMATE FSI VALUES OF SELECTED MATERIALS

Interior finish material	FSI	Interior finish material	FSI
Fiberglass (kraft paper facing)	0–5	Red oak	100
Fiberglass (aluminum foil facing)	0–5	Southern pine	130–190
Shredded wood fiber board	20–25	Douglas fir	70–100
Spray-on cellulosic fibers (treated)	20	Plywood paneling	75–275
Cement board	0	Fire-retardant treated lumber	<25
Bricks or concrete masonry	0	Cork	175
Concrete	0	Carpets	10–600
Gypsum board (paper facing)	10–25		

Source: Several sources.

A material whose FSI is 200 means that the rate of flame spread on this material is twice as rapid as that on red oak. Similarly, on a material whose FSI is 50, the rate of flame travel is half as rapid as that on red oak. Table 7.1 gives approximate FSI values of some commonly used building materials. Building codes limit the maximum value of FSI to 200 for an interior finish material.

SMOKE-DEVELOPED INDEX (SDI)

The smoke-developed index (SDI) measures the visibility through the smoke resulting from burning assemblies or materials used as interior finishes. The lower the visibility through smoke is, the greater is the SDI value. SDI values of materials are obtained from the same test as the FSI. The SDI is also measured on a scale that begins at zero but has no upper limit. Once again, the SDI value of red oak has been arbitrarily fixed at 100, and that of Portland cement board is fixed at zero.

Building codes at the present time do not require the toxic effects of smoke to be rated, except for prohibiting the use of some materials as interior finishes because of the excessive toxicity of their smoke. The only building code requirement of the smoke generated by materials is that the SDI value of a material used as an interior finish should not exceed 450.

TABLE 7.2 CLASSIFICATION OF INTERIOR FINISHES

Flame spread class	FSI	SDI
Class A	0–25	≤450
Class B	26–75	≤450
Class C	76–200	≤450

Source: 2015 International Building Code, p. 203.

BUILDING CODE REQUIREMENTS FOR FSI AND SDI

Based on FSI and SDI values, building codes classify interior finishes into three classes: Class A, Class B, and Class C, Table 7.2. The objective of this classification is to regulate the use of interior finish materials according to the fire safety requirements of spaces. Because Class A interior finishes are the least hazardous, building codes mandate that they be used in enclosed vertical exit ways—staircases and elevators. A minimum of Class B interior finish material is required in exit access spaces (corridors, lounges, foyers, and so on). Class C finishes may be used in areas such as individual rooms, Figure 7.19.

There are a few exceptions to these rules, for which the applicable building code should be consulted. For example, Class C materials are allowed to be used in all areas of a single-family dwelling, even in stair enclosures and corridors. Additionally, the provision of automatic sprinklers in a building allows Class B finishes to be used in vertical exit areas where Class A is generally needed.

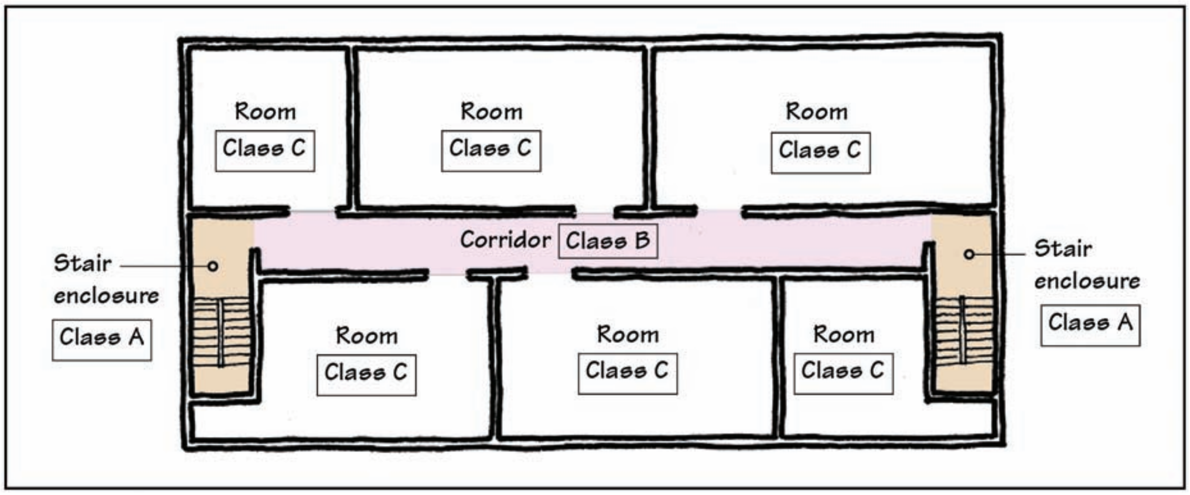


FIGURE 7.19 Minimum building code requirements for the class of interior finishes on walls and ceilings.

No classification is given to interior finishes with an FSI >200 or an SDI >450, because these materials are not allowed as interior finish materials except in utility occupancies. Only finishes applied on walls and ceilings are regulated for FSI and SDI values. Floor finishes such as carpets and floor tiles are not rated for FSI or SDI.

FIRE AND FLOOR FINISHES

Because flames spread vertically upward, floor finishes do not get involved in a building fire until fairly late in the burning process. Therefore, most traditional nonfibrous floor finishes, even the combustible finishes (such as wood, vinyl, and linoleum), are exempt from any fire-related properties. However, the fire properties of carpets and rugs are regulated, and they must pass the pill test.

NOTE

Pill Test

The pill test simulates the effect of a lighted cigarette, match, or fireplace ember on a carpet or rug. In the test, a methenamine tablet is placed on the carpet or rug specimen, and the tablet is ignited with a match. If the specimen burns more than 3 in. in any direction from the location of the tablet, the specimen fails the test.

FIRE AND ROOF COVERINGS

Although roof coverings (required for the waterproofing of roofs) are exterior to the building, their fire properties are regulated because their burning can pose a hazard to an adjacent building or an adjacent part of the same building. The reverse may also occur in that the burning embers of roof-covering material on a building may land on an adjacent building. Roof-covering materials are classified as Class I, Class II, or Class III (per ASTM standard E108), Class I being the most fire resistive and Class III the least fire resistive. Building codes mandate a higher class of roof-covering material for a more fire-resistive type of construction.

FIRE RESISTANCE AND SURFACE FLAMMABILITY

Note that the fire rating of assemblies and the surface-burning properties of interior finishes and roof coverings are entirely independent and unrelated properties. Whereas the fire rating is a measure of the structural integrity of a barrier during a fire, the surface-burning properties (e.g., FSI and SDI) measure the fire hazard of an interior finish material. For example, heavy timber construction may give the equivalent of 1 h or more of fire rating, but it presents some degree of hazard as an interior finish. A thin steel plate, on the other hand, is a poor fire barrier with a virtually zero fire rating, but presents no hazard as an interior finish material.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

21. The term *FSI* refers to
  a. fire safety index.
  b. fire and smoke index.
  c. fire-speed index.
  d. flame-spread index.

22. SDI measures
  a. visibility through smoke.
  b. toxicity of smoke.
  c. rate of smoke generation.
  d. amount of carbon dioxide in smoke.
  e. none of the above.

23. Based on their fire properties, interior finishes are divided into
  a. Classes I, II, III, and IV.
  b. Classes A, B, C, and D.
  c. Classes W, X, Y, and Z.
  d. Classes A, B, and C.
  e. Classes X, Y, and Z.

24. The fire properties that determine the class of interior finishes are
  a. fire-resistance rating and FSI.
  b. FSI and SDI.
  c. fire-resistance rating and SDI.
  d. fire-resistance rating, FSI, and SDI.

25. The maximum value of SDI recognized by building codes is
  a. 450.
  b. 300.
  c. 150.
  d. 50.
  e. none of the above.

26. FSI of cement board is
  a. 200.
  b. 100.
  c. 50.
  d. 20.
  e. zero.

27. The spread of flames on floor finishes is ignored.
  a. True
  b. False

7.9 ESSENTIALS OF PASSIVE FIRE PROTECTION—COMPARTMENTALIZATION OF BUILDING

As discussed earlier, the type of construction classification of buildings is based on the fire ratings of the structural assemblies of buildings. This is because the structural integrity of a building subjected to fire is fundamental to safety. The next most important aspect of fire safety is compartmentalization of building.

Compartmentalization implies subdividing a building into compartments where each compartment is bounded by fire-rated assemblies, Figure 7.20. Its purpose is to confine the fire to the compartment of its origin so that fire's spread through other parts of the building

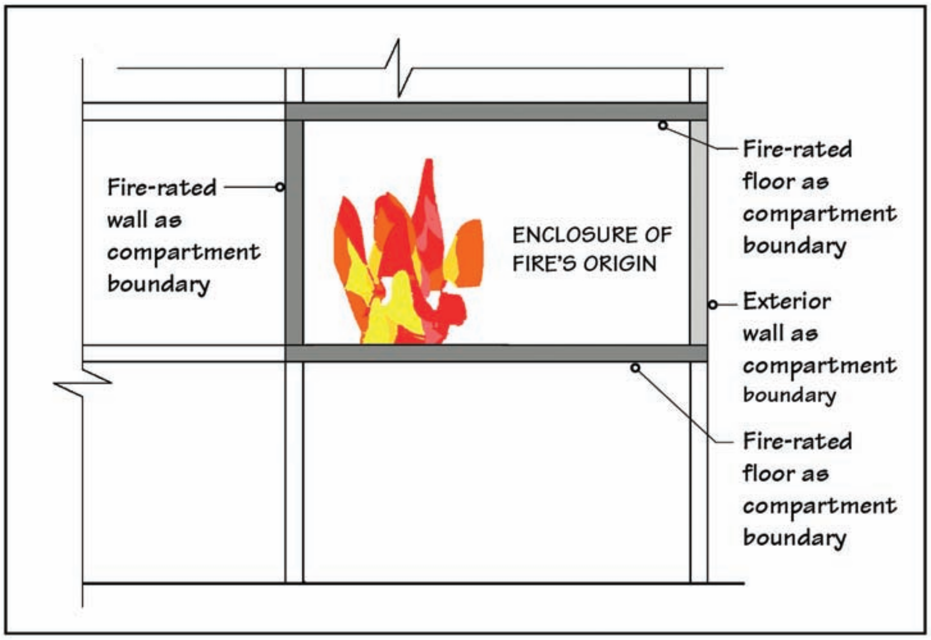

Fire-rated wall as compartment boundary
ENCLOSURE OF FIRE'S ORIGIN
Fire-rated floor as compartment boundary
Exterior wall as compartment boundary
Fire-rated floor as compartment boundary

FIGURE 7.20 Compartmentalizing spaces and volumes of a building and enclosing them with fire-rated interior walls, fire-rated horizontal assemblies (floors/roof), and exterior walls are an important passive fire protection strategy. Note that the exterior walls may or may not require any fire rating, as explained in the text and Figure 7.27.

is delayed to allow firefighting measures to come to action. Therefore, compartmentalization increases fire safety for the occupants and also reduces the extent of property damage. The principal assemblies that help make up the compartments are:

- Fire-rated wall assemblies
- Fire-rated horizontal assemblies
- Exterior walls

FIRE-RATED WALL ASSEMBLIES

Various types of fire-rated wall assemblies are used in compartmentalizing a building, each with a different function, as described hereunder.

FIRE WALLS: A fire wall is the ultimate strategy in compartmentalizing a building. It is defined as a fire-rated wall that divides a building into two structurally separate buildings so that if the building on one side of the wall burns down and collapses, the building on the other side of the fire wall (and the wall itself) remains intact, Figure 7.21.

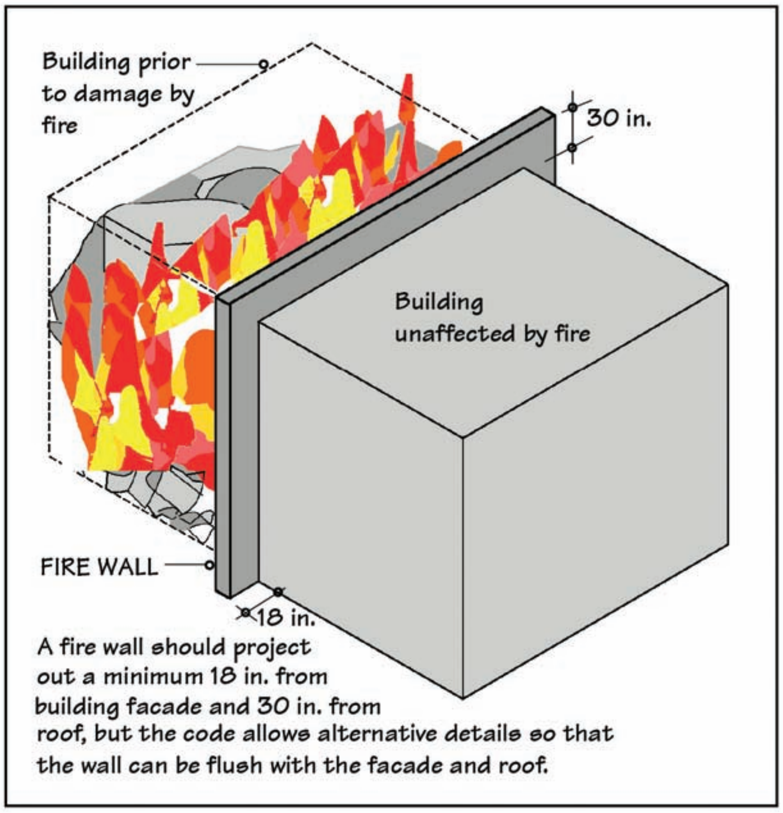

Building prior to damage by fire
30 in.
Building unaffected by fire
FIRE WALL
18 in.
A fire wall should project out a minimum 18 in. from building facade and 30 in. from roof, but the code allows alternative details so that the wall can be flush with the facade and roof.

FIGURE 7.21 A fire wall divides a building into two structurally independent buildings, and has sufficient fire resistance to allow the building on one side of the wall, and the wall itself, to remain intact while the building on the other side of the wall may burn down and collapse.

To perform this function, a fire wall must have sufficient structural integrity to stay intact as a freestanding wall for a prescribed duration in spite of the failure of automatic sprinklers and (or) the nonavailability of firefighting measures. It must extend from foundation to the roof or above the roof, and from exterior wall to exterior wall. It should also be of noncombustible materials (except in Type V construction). The fire rating required of a fire wall is 2 h, 3 h, or 4 h, depending on the building's occupancy.

Because a fire wall divides a building into two separate buildings, it is used as a party wall between buildings, such as between adjacent townhouses. Additionally, building codes regard a building with a fire wall as consisting of two totally independent buildings as if they are separated by a large open space between them. Therefore, each of the two separated buildings is permitted to have its own allowable area. Because a fire wall subdivides a building into two smaller-area, independent buildings and because a smaller-area building can be constructed with a lower type of construction, the use of fire walls may reduce construction cost and building's footprint.

FIRE BARRIERS: A fire barrier belongs to the next level below a fire wall in compartmentalizing a building. Unlike a fire wall, which must be continuous from foundation to roof, a fire barrier needs to be continuous from the supporting floor to the next floor (or roof) above, and must be securely attached to it, Figure 7.22.

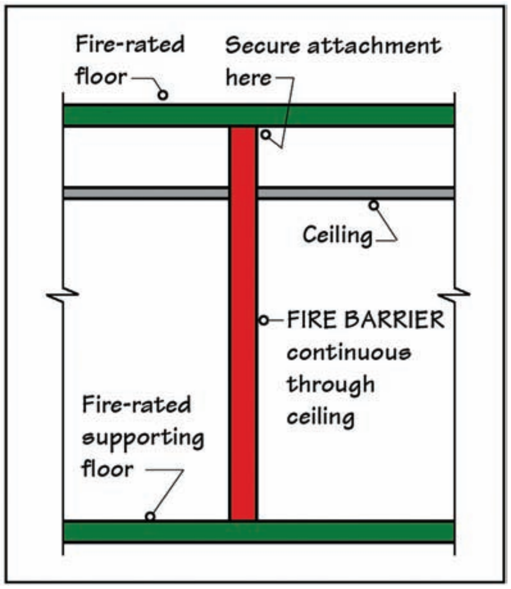

Fire-rated floor
Secure attachment here
Ceiling
FIRE BARRIER continuous through ceiling
Fire-rated supporting floor

FIGURE 7.22 A fire barrier extends uninterrupted to the floor or the roof above (through the ceiling, if any) to provide a continuous separation from one compartment to the other. The supporting floor must have at least the same fire rating as the fire barrier, but not less than that required for the type of construction given in Figure 7.11.

Fire barriers are used in enclosing: (a) elevator shafts, (b) exit stairway shafts, (c) exit access stairways, and (d) exit passageways, Figure 7.23. The minimum fire rating of fire barriers for aforesaid uses is 2 h if the number of stories in a building ≥4, and 1 h if the number of stories ≤3.

Fire-rated walls separating two different occupancies in a separated mixed-occupancy building are also known as *fire barriers*, Figure 7.24. Their minimum fire rating is 1 h, 2 h, 3 h, or 4 h depending on the occupancies being separated. (See section 2.7 for the difference between a separated mixed-occupancy and a nonseparated mixed-occupancy building.)

FIRE PARTITIONS: A fire partition belongs to the next level below fire walls and fire barriers in building compartmentalization. Fire partitions are commonly used in exit access corridors, and must have a minimum fire rating of 1 h. Some other situations where fire partitions are required are tenant separations in covered malls and dwelling unit separations in the same building.

In several occupancies (A, B, E, F, M, S, and U), the required rating of fire partitions, as corridor walls, is zero if the building is sprinklered. A fire partition must extend from supporting floor to the underside of roof or floor deck above (or a fire-rated ceiling) in a nonsprinklered building. In a sprinklered building, a fire partition, as a corridor wall, may terminate at a smoke-resistant ceiling, Figure 7.25.

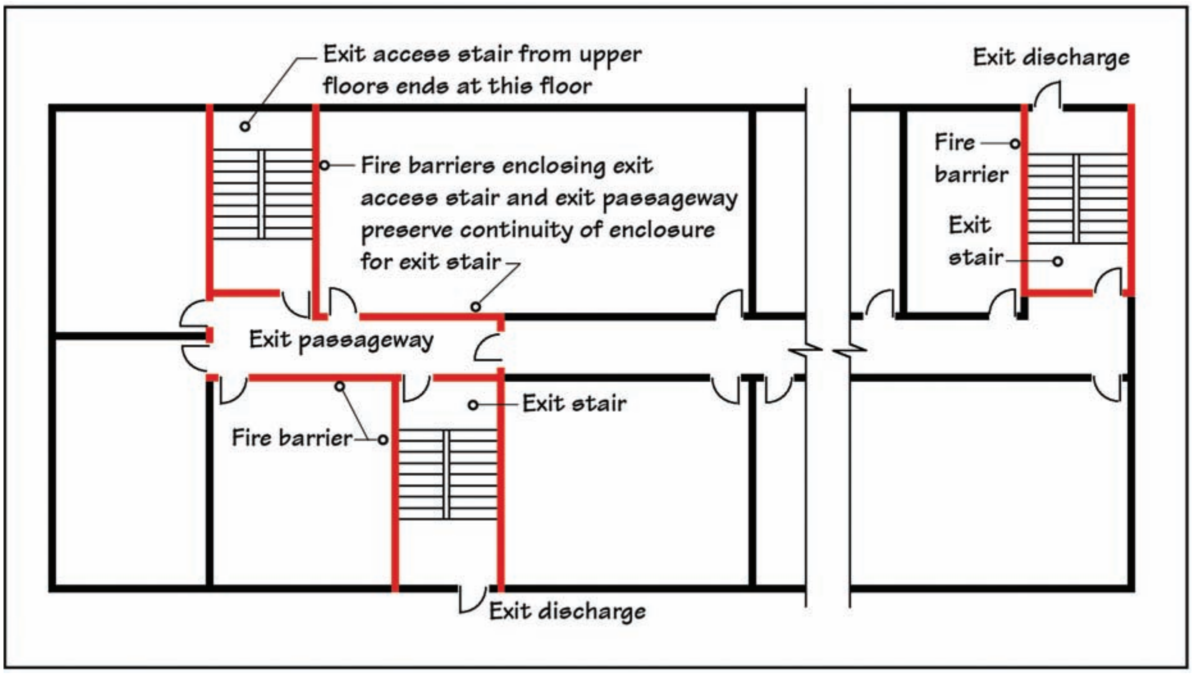

Exit access stair from upper floors ends at this floor
Exit discharge
Fire barriers enclosing exit access stair and exit passageway preserve continuity of enclosure for exit stair
Fire barrier
Exit stair
Exit passageway
Exit stair
Fire barrier
Exit discharge

FIGURE 7.23 Fire barriers around exit stair separate it from the building area, and are required to have a minimum fire rating of 2 h if connecting ≥4 stories and 1 h for ≤4 stories.

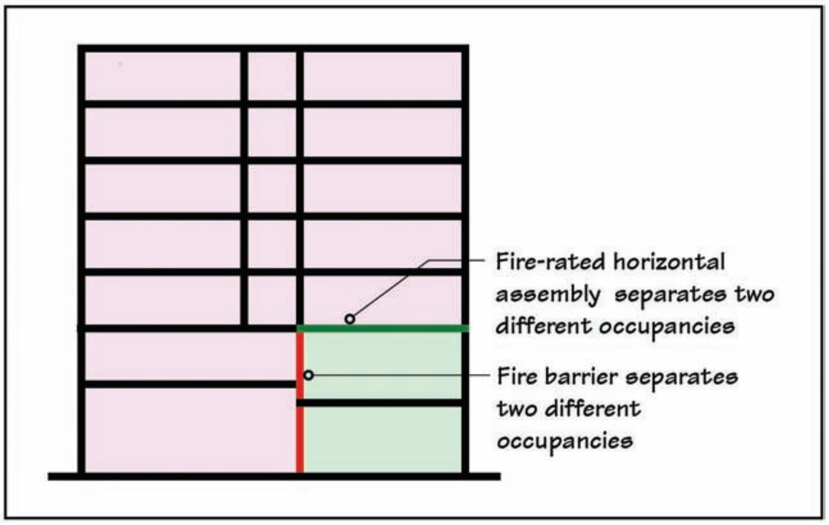

Fire-rated horizontal assembly separates two different occupancies
Fire barrier separates two different occupancies

FIGURE 7.24 Section through a building with two different occupancies distinguished by purple and green colors. Fire barriers are required to separate one occupancy from the other if they are separated occupancies. The fire rating of fire barriers as occupancy separation range from 1 h to 4 h. The fire rating of horizontal assembly, used as occupancy separation, must match or exceed the rating of fire barrier, but not less than that required for the building's type of construction (see Figure 7.11).

FIRE-RATED HORIZONTAL ASSEMBLIES

Because floors and roof are structural assemblies, their fire-rating requirements are governed by the building's type of construction classification (given in Figure 7.11). However, where a horizontal assembly is used in conjunction with a fire barrier for compartmentalization, its fire rating must at least equal that of the fire barrier. In other words, the fire rating of a horizontal assembly must equal or exceed the rating of the related fire barrier and also that required by the building's type of construction. Thus in Figure 7.24, the fire rating of horizontal assembly (shown in green) is related to rating of the fire barrier (shown in red), and also the rating required by the building's type of construction.

A building type that has become fairly popular in recent years is known as a *podium building*. In this building type, the podium must be of Type I(A) construction (generally constructed of cast-in-place reinforced concrete) and supports a few floors of multifamily structure in wood frame, Figure 7.26. The building codes require that the podium floor (the horizontal assembly below the wood floor structure) must have a minimum fire rating of 3 h, which is greater than the 2-h rating required of a floor assembly in Type I(A) construction. The construction details of podium type buildings are discussed in Chapter 17.

EXTERIOR WALLS

An exterior wall can provide a barrier to the spread of fire even if it is not fire rated. This is true only if there is no adjacent building close to the exterior wall, or if the exterior wall is sufficiently far away from the property line (the neighboring property can extend to the property line). If the exterior wall is close to the property line or an adjacent building, the exterior wall must be fire rated.

The minimum required rating of an exterior wall is 3h, 2h, 1 h, or zero, and is primarily a function of its distance from the property line, centerline of public way (or an adjacent building on the same property), referred to as the *fire separation distance* (FSD), Figure 7.27. For a nonsprinklered building, the exterior wall may be nonrated if FSD ≥30 ft, regardless of the building's occupancy or type of construction. For a sprinklered building, the corresponding value of FSD is 20 ft. For a load-bearing exterior wall, however, the fire rating based on the building's type of construction must also be taken into account. It is because of the zero fire rating requirement (based on FSD) that several buildings are clad with all-glass curtain walls, whose fire rating is virtually zero.

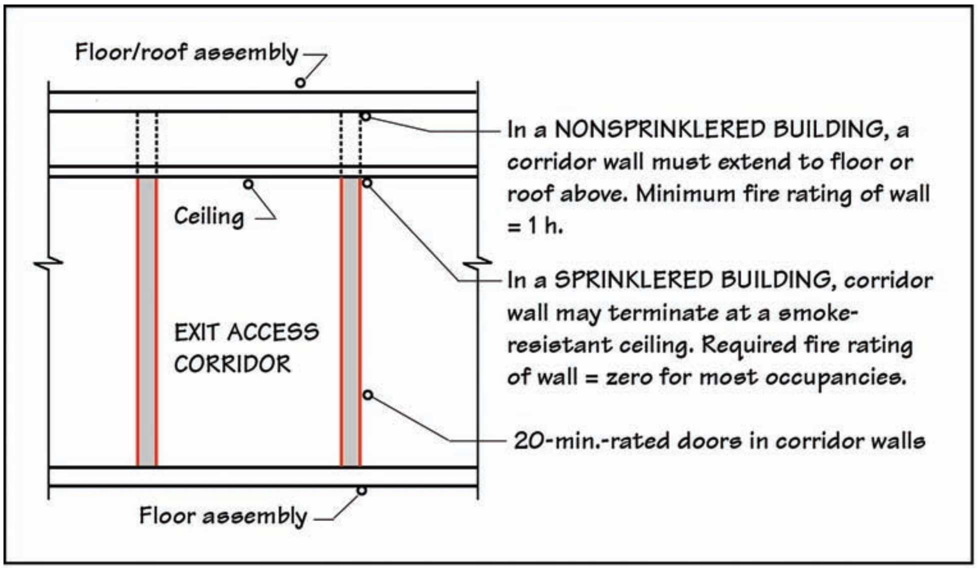

Floor/roof assembly
In a NONSPRINKLERED BUILDING, a corridor wall must extend to floor or roof above. Minimum fire rating of wall = 1 h.
Ceiling
In a SPRINKLERED BUILDING, corridor wall may terminate at a smoke-resistant ceiling. Required fire rating of wall = zero for most occupancies.
EXIT ACCESS CORRIDOR
20-min.-rated doors in corridor walls
Floor assembly

FIGURE 7.25 Section through an exit access corridor, showing corridor walls as fire partitions.

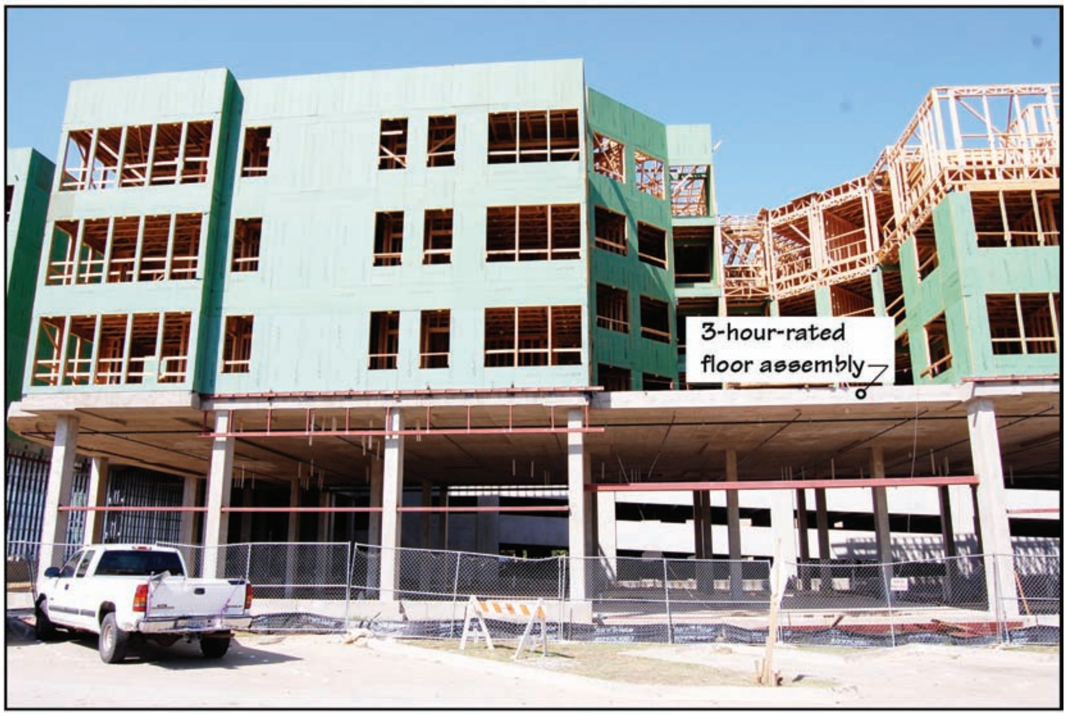


FIGURE 7.26 A typical podium-type building with multifamily residential (wood frame) structure above a multi-use structure in Type I(A) construction. In this building, the minimum fire rating of the horizontal assembly separating the two structures is 3 h.

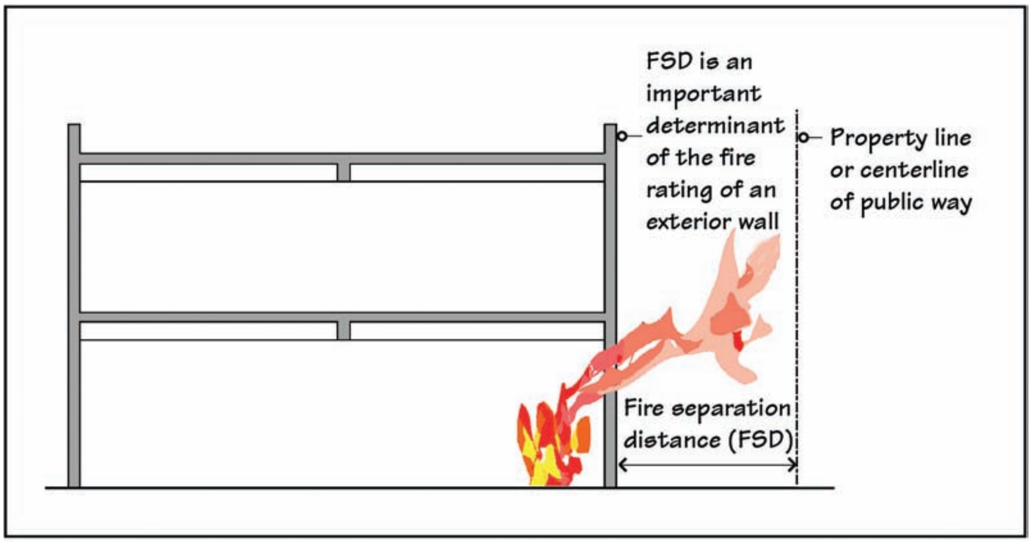

FSD is an important determinant of the fire rating of an exterior wall
Property line or centerline of public way
Fire separation distance (FSD)

FIGURE 7.27 The fire rating of an exterior wall is a function of its fire separation distance (FSD). For a nonsprinklered building, the exterior wall may be nonrated regardless of the building's occupancy classification or its type of construction if FSD ≥ 30 ft. For a sprinklered building, the corresponding value of FSD is 20 ft. It is because of this provision in building codes that buildings can be fully clad with nonrated exterior walls, such as all glass walls. However, if the exterior wall is a load-bearing wall, its fire rating must meet the requirement specified for the building's type of construction.

7.10 ESSENTIALS OF PASSIVE FIRE PROTECTION—OPENING PROTECTION AND FIRE SEALING OF PENETRATIONS AND JOINTS

It is obvious that for an assembly to retain its fire rating, the openings (doors and windows) in it must also be fire rated. Therefore, doors, windows, spaces around penetrations through an assembly, and joints between assemblies need to be fire rated as well.

FIRE-RATED DOORS AND WINDOWS

The fire endurance of doors and windows is referred to as *fire protection rating* to distinguish it from the term "fire-resistance rating" because the test standard used for determining the rating of doors and windows is not the same as for the structural assemblies (walls, floor, and roof assemblies, described in Section 7.5). The required fire protection rating of doors and windows is generally less than the rating of walls in which they are used. This is based on the premise that a wall may have combustibles stored against it, while the probability of such storage against doors and windows is remote. Thus, the protection rating of a door assembly in a 2-h rated exit stairway is 1.5 h. A 1-h rated corridor wall requires a 20-min rated door assembly (see Figure 7.25).

THROUGH-PENETRATION FIRESTOPS

The penetrations through a fire-rated assembly must be sealed because an unsealed space will allow heat, smoke, and flammable gases to move from one side of the assembly to the other, compromising the assembly's fire rating. The fire rating of seals (referred to as *firestops*) is generally required to match the fire rating of the assembly in which they are installed.

Fire-stopping materials must obviously be noncombustible. Several are in common use. They generally consist of mineral wool topped with fire-resistant semi-liquid sealants, Figure 7.28. Fire-stop materials also help to seal spaces against air and sound transmission.

JOINT SEALS BETWEEN FLOORS AND EXTERIOR CURTAIN WALLS

Just as penetrations through a fire-rated building element are required to be fire-stopped, joints in them (such as expansion joints and control joints, Chapter 9) are also required to be sealed with a fire-rated joint assembly. Similarly the space between a curtain wall and a fire-rated floor or roof also needs to be fire-sealed. (See Chapter 27 for the definition of a curtain wall.) In fact, the entire spandrel assembly in a curtain wall (extending from the head of the window at a floor to the sill of the window above that floor) must be fire-sealed to provide protection for the same duration as the fire rating of the floor, Figure 7.29(a).

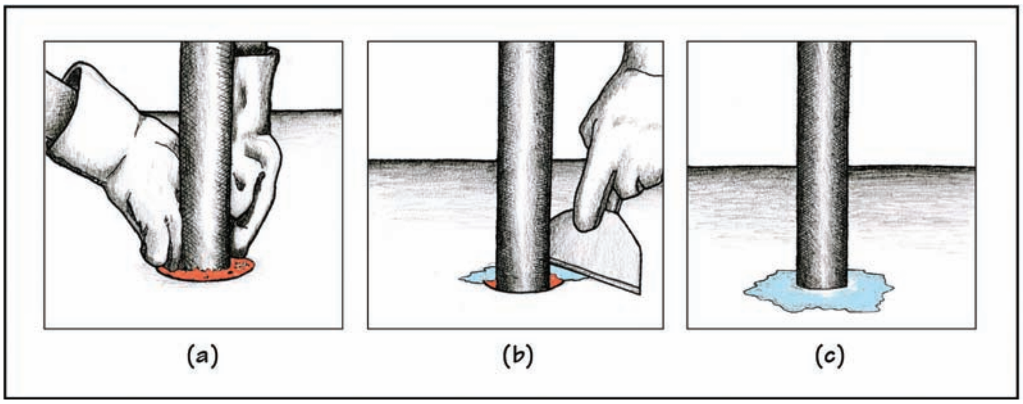
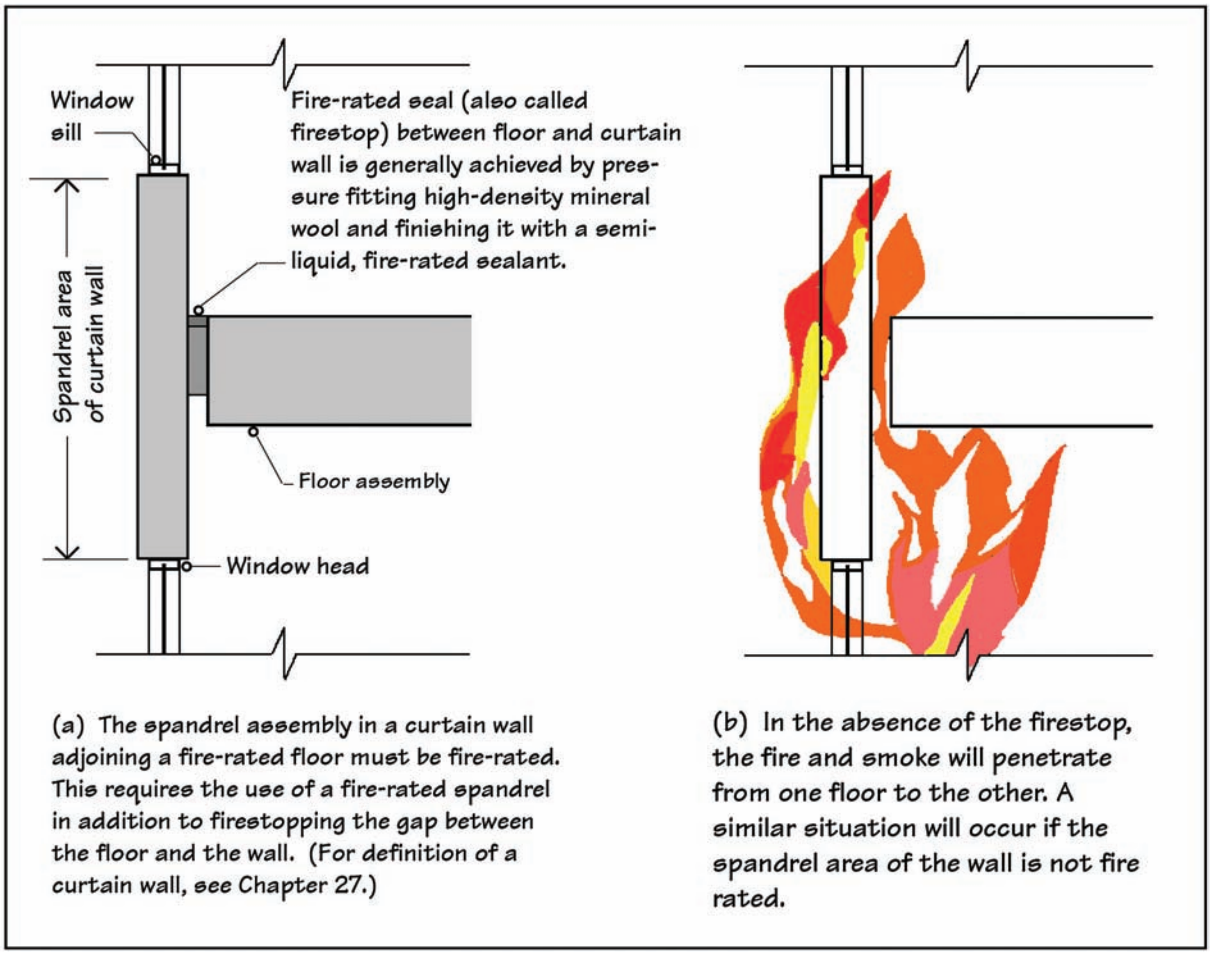


FIGURE 7.28 A typical firestop around a penetration in a floor generally consists of high-density mineral wool pressure packed into the void, followed by a semi-liquid, fire-resistant sealant troweled over mineral wool packing. **(a)** Pressure packing of mineral wool, **(b)** troweling of sealant over mineral wool packing, and **(c)** finishing of sealant flush with floor surface.


Window sill
Fire-rated seal (also called firestop) between floor and curtain wall is generally achieved by pressure fitting high-density mineral wool and finishing it with a semi-liquid, fire-rated sealant.
Spandrel area of curtain wall
Floor assembly
Window head

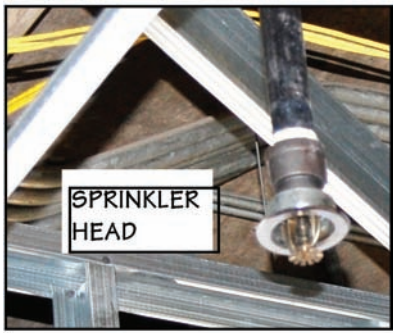
(a) The spandrel assembly in a curtain wall adjoining a fire-rated floor must be fire-rated. This requires the use of a fire-rated spandrel in addition to firestopping the gap between the floor and the wall. (For definition of a curtain wall, see Chapter 27.)

(b) In the absence of the firestop, the fire and smoke will penetrate from one floor to the other. A similar situation will occur if the spandrel area of the wall is not fire rated.

FIGURE 7.29 Fire containment assembly in a curtain wall consists of a fire-rated spandrel and fire-rated seal between wall and floor.

In the absence of a fire-rated spandrel and (or) a fire-rated seal in the wall-floor gap, the fire, heat, and smoke from the lower floor will not be contained within the floor of origin, Figure 7.29(b). Although the requirements of a fire seal between the curtain wall and a non-fire-rated floor or roof assembly are less stringent, a fire seal is required all the same to prevent the passage of smoke and hot gases.

7.11 ESSENTIALS OF ACTIVE FIRE PROTECTION



As previously stated, active fire protection (through the use of automatic sprinklers) is an important part of fire-safe construction. Building codes provide incentives in the use of automatic sprinklers by allowing greater area and height for a building that is sprinklered (see Chapter 2, Principles in Practice) in comparison with a building that is not sprinklered.

WHERE AUTOMATIC SPRINKLERS MANDATED

Apart from the incentives, building codes mandate the use of automatic sprinklers in several situations; the more important ones are mentioned here. For example, if a building has a floor (with an occupant load ≥30) and located ≥55 ft above the lowest level of fire department's vehicle access, sprinklers are required throughout the building regardless of the building's occupancy and type of construction, Figure 7.30. Additionally, covered malls, atriums, apartment buildings, and so on, are required to have automatic sprinklers. In several states, one- and two-family dwellings and townhouses are also required to be sprinklered.

AUTOMATIC SPRINKLER TRADE-OFFS WITH PASSIVE PROTECTION

Realizing the substantial increase in fire safety provided by sprinklers, the building codes allow reduction in fire-resistance rating of assemblies if sprinklers are provided. For example, as shown in Figure 7.25, the provision of automatic sprinklers in the building allows the complete elimination of fire rating requirement for corridor walls for most occupancies. Sprinklers also allow the lowering of the class of interior finish materials (from Class A to Class B or from Class B to Class C) in several situations.

FIRE BARRIERS AND FIRE AREA: One of the most important trade-offs between automatic sprinklers and passive protection lies in the concept of fire compartment, called *fire area* in building codes. The codes require that if the fire area in a building exceeds a certain amount, it must be provided with automatic sprinklers. The fire area threshold amount varies with building's occupancy. A fire area is defined as the area bounded by fire-rated horizontal assemblies, fire walls, fire barriers, or exterior walls.

As an example, consider a one-story furniture warehouse (Occupancy S-1) with 22,000 sq ft area, bounded on all sides by exterior walls, Figure 7.31. In other words, the warehouse consists of a single fire area of 22,000 sq ft. The fire area threshold amount for Occupancy S-1 is 12,000 sq ft. Therefore, the warehouse would require automatic sprinklers. However, if we provide a fire barrier to subdivide the space into two fire areas of 12,000 sq ft or less (say 11,000 sq ft each), the use of automatic sprinklers is unnecessary.

The fire rating requirement of fire barriers for fire area subdivision is 4 h , 3 h, 2 h, or 1 h, depending on building's occupancy. For Occupancy S-1, the requirement is 3h. (It is

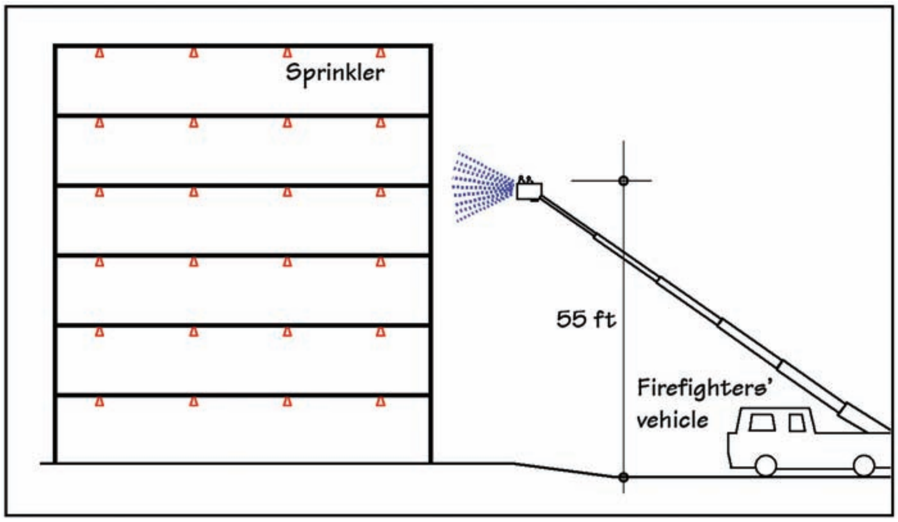


FIGURE 7.30 If a building contains an occupant load of ≥30 at a height ≥55 ft, as measured from the lowest level of firefighters' vehicle access, the entire building must be provided with automatic sprinklers. Effectively, this provision requires that all mid-rise and taller buildings must be fully sprinklered.

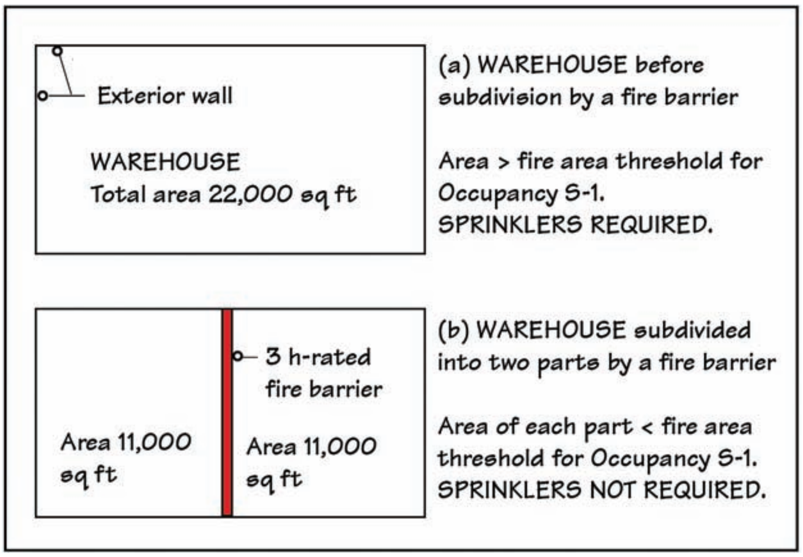

Exterior wall
WAREHOUSE
Total area 22,000 sq ft
(a) WAREHOUSE before subdivision by a fire barrier
Area > fire area threshold for Occupancy S-1.
SPRINKLERS REQUIRED.
3 h-rated fire barrier
Area 11,000 sq ft
Area 11,000 sq ft
(b) WAREHOUSE subdivided into two parts by a fire barrier
Area of each part < fire area threshold for Occupancy S-1.
SPRINKLERS NOT REQUIRED.

FIGURE 7.31 Fire area, defined as the area enclosed and bounded by exterior walls, fire walls, fire barriers, and fire-rated horizontal assemblies, is one of the determinants of whether the sprinklers are mandated by building codes.

important to note here that the use of automatic sprinklers may also be triggered by factors other than fire area considerations and mandated in several situations, as previously mentioned.)

TYPES OF AUTOMATIC SPRINKLER SYSTEMS

United States building codes recognize three types of automatic sprinkler systems: (a) NFPA 13, (b) NFPA 13R, and (c) NFPA 13D. (Note: NFPA is an acronym for National Fire Protection Association.) Of the three types, NFPA 13 system has the most stringent specifications, and is commonly required. NFPA 13R system can be used only in Group R occupancies (residential) up to 4 stories, not exceeding 60 ft in height. NFPA 13D can be used only in one- and two-family dwellings and townhouses. Note that the increase in maximum allowable building area, height, and number of stories shown in Figures 2.25 and 2.26 is available only where NFPA 13 is used, regardless of the building's occupancy.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

28. A fire wall divides a building into two parts in such a way that
- **a.** the aggregate area of each part is the same.
- **b.** the occupant load in each part is the same.
- **c.** if the automatic sprinklers have been installed in one part, it is as if they have been installed in both parts.
- **d.** the two parts behave as two separate buildings so that if one part burns down and collapses along with the fire wall, the other part will remain intact.
- **e.** the two parts behave as two separate buildings so that if one part burns down and collapses, the other part and the fire wall will remain intact.

29. A fire wall must be constructed of noncombustible materials with no exceptions.
- **a.** True
- **b.** False

30. A fire barrier refers to a
- **a.** fire-rated floor.
- **b.** fire-rated roof.
- **c.** fire-rated wall.
- **d.** all of the above.
- **e.** none of the above.

31. The walls enclosing an exit stair are generally designed as
- **a.** fire walls.
- **b.** fire barriers.
- **c.** fire partitions.
- **d.** any one of the above.
- **e.** none of the above.

32. The exit access corridor walls in most occupancies need not be fire rated if the building is provided with automatic sprinklers throughout.
- **a.** True
- **b.** False

33. The term firestop refers to
- **a.** a fire-rated wall with a minimum fire rating of 3 h.
- **b.** a fire-rated floor with a minimum fire rating of 3 h.
- **c.** a fire seal in a non-fire-rated wall or floor.
- **d.** a fire seal in a fire-rated wall or floor.
- **e.** none of the above.

34. A rectangular area of building that is bounded on all three sides by exterior walls, on the fourth side by a fire barrier, and with fire-rated floors above and below, may be treated as a fire area.
- **a.** True
- **b.** False

PRINCIPLES IN PRACTICE

Materials Used for Passive Fire Protection

An essential requirement of a material to provide passive protection (fire-resistance rating) in an assembly is that it should be noncombustible. Concrete and masonry (brick, stone, and concrete masonry), being noncombustible, provide a high degree of fire rating if used in sufficient thickness. Wood and steel are not in the same category, because wood is a combustible material and steel loses strength substantially if exposed to high temperatures present in a typical building fire.

GYPSUM BOARD

Therefore, wood and steel assemblies must be provided with noncombustible add-on materials to obtain the required fire rating. The most commonly used such material is gypsum, generally used in board formation (as gypsum board). Gypsum board is used in both wood and steel assemblies. A detailed discussion of gypsum board, as a fire-resistive material, is given in Section 16.5, and the fire ratings of assemblies using gypsum board are given in Section 16.7 (for wood frame assemblies), Section 18.8 (for structural steel assemblies), and Section 20.13 (for cold-formed steel assemblies).

SPRAY-APPLIED FIRE PROTECTION

In addition to noncombustibility, another material property that is exploited to provide (or increase) fire-resistance rating of assemblies is insulation. Because insulation retards the flow of heat, it delays the assemblies' failure when exposed to fire. A commonly used fire protective insulating material is a mix comprising mineral wool (or fiberglass) and Portland cement. This mix is commonly used as a spray-applied material on structural steel, and is covered in Section 18.7. Note that only noncombustible insulation can be used for fire-resistance purposes.

REVIEW QUESTIONS

1. List the factors that affect fire safety in buildings.
2. Discuss the differences between a fire code and a building code.
3. Explain why we need a test standard to determine whether a building material is combustible or noncombustible when we generally know which material is combustible and which is noncombustible.
4. Using a sketch and notes, explain how the fire-resistance rating of an assembly is determined using ASTM standard E119.
5. List the building assemblies that determine the type of construction classification of a building.
6. List the three groups in which the types of construction of buildings are divided based on whether the materials used in assemblies are combustible or noncombustible.
7. What is the difference between Type III(A) and Type IV construction? Explain.
8. Using Figure 7.11, determine the type of construction of a building with the following data:
   Structural frame; structural steel; 2-h rated
   Floors; steel joists, steel deck, and concrete topping; 1-h rated
   Roof; steel deck; 2-h rated
   Exterior bearing walls; none provided
   Interior bearing walls; none provided
9. What is the type of construction of the building of Problem 8 if the floor's fire rating is 2 h, while all else remain unchanged?
10. Describe the differences between Class A, Class B, and Class C interior finishes based on FSI and SDI.
11. Using a sketch and notes, explain what a fire wall is.
12. Using a sketch, explain the concept of fire separation distance and its effect on the required fire-resistance rating of an exterior wall.
13. Explain the differences between the automatic sprinkler systems: NFPA 13, NFPA 13R, and NFPA 13D.
14. Explain the term "fire area".
15. Name two materials that are commonly used to provide or increase the fire-resistance rating of assemblies.

CHAPTER 8

Acoustical Properties of Materials

CHAPTER OUTLINE

8.1 FREQUENCY, SPEED, AND WAVELENGTH OF SOUND

8.2 THE DECIBEL SCALE

8.3 AIRBORNE AND STRUCTURE-BORNE SOUNDS

8.4 AIRBORNE SOUND INSULATION—SOUND-TRANSMISSION CLASS

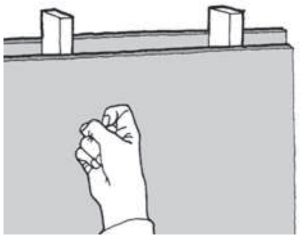
8.5 STRUCTURE-BORNE SOUND INSULATION—IMPACT INSULATION CLASS

8.6 SOUND ABSORPTION—NOISE-REDUCTION COEFFICIENT

Acoustical and noise-control concerns exist in almost every modern building. An acoustical consultant is usually required for the design of an auditorium or a concert hall or for the solution of a complicated noise problem. However, commonplace acoustical issues in most buildings, such as selecting the appropriate interior finishes for a lecture room, controlling noise in a busy dining hall, or isolating a hotel bedroom from street noise, are fairly elementary and are resolved by design professionals without a consultant's help.

This chapter provides an understanding of the acoustical properties of materials and assemblies that are routinely used in buildings. It begins with a discussion of the basic characteristics of sound waves (frequency, speed, and wavelength), leading to the decibel scale— a unit for rating the loudness of sound. This is followed by a discussion of the sound-insulation and sound-absorbing properties of materials.

8.1 FREQUENCY, SPEED, AND WAVELENGTH OF SOUND


A tap on a wall makes the wall vibrate, which in turn makes the air particles vibrate, producing sound waves.

Sound is the human ear's response to pressure fluctuations in the air caused by vibrating objects. For example, a tap on a wall produces sound because the tap makes the wall vibrate back and forth. The back-and-forth motion of the wall is transferred to air particles in direct contact with the wall. These particles then transfer their vibratory motion to the neighboring particles, and so on.

The domino-type transfer of vibratory motion from particle to particle is what we refer to as a *sound wave*. The number of back-and-forth cycles that an object (or the air particles) moves in 1 s in a sound wave is called *sound frequency*. Its unit is cycles per second (c/s), which is also termed *hertz* (Hz) after the Austrian physicist Heinrich Hertz. Vibrations with frequencies lying between 20 Hz and 20,000 Hz (i.e., 20 kHz) are audible. This range of frequencies is called the *audible frequency range*.

Subjectively, the frequency of a sound is perceived as its pitch. A high-pitched sound means that it has a high frequency. A female voice is slightly higher pitched than a male voice.

Sounds in our environment do not generally consist of individual frequencies (a single note or pure tone), such as that produced by a tuning fork. Most sounds are complex; that is, they consist of a continuum of several frequencies. Thus, the human speech consists of all frequencies ranging from nearly 200 Hz to 5 kHz. The male voice peaks at about 400 Hz, and the female voice peaks at about 500 Hz. The range of frequencies in music is larger than the range for speech.

Frequency of sound is an important acoustical concept because the properties of building materials and construction assemblies are frequency dependent, meaning that building products vary in how they transmit or absorb sound in its many frequencies.

NOTE

Cycles per Second and Hertz

Hertz (Hz) and cycles per second (c/s) are used interchangeably, that is,

1 Hz = 1 c/s
1,000 Hz = 1 kilohertz = 1 kHz

SPEED OF SOUND

The speed of sound in the air has been measured as 1,130 ft/s (344 m/s) and is independent of sound frequency or loudness. Because sound travels from particle to particle in a medium, a medium is required for the existence of sound. In other words, sound cannot be produced or travel in a vacuum. This is in contrast with light and heat waves, which, being electromagnetic in nature, do not require a medium for travel.

NOTE

Speech Sounds

Human speech lies in the frequency range of 200 Hz to 5 kHz. However, most of the speech energy lies in the range of 250 Hz to 2 kHz.

WAVELENGTH OF SOUND

As a sound wave travels, it creates excess pressure (called *compression*) and reduced pressure (called *rarefaction*) in space, just as water waves produce *crests* and *troughs*. The distance between adjacent compression peaks or adjacent rarefaction peaks in the air at an instant of time is called the *wavelength*. The frequency, wavelength, and speed of wave motion are related to each other by the following simple relationship:

$$\boxed{\text{Speed} = \text{frequency} \times \text{wavelength}} \qquad \textbf{Eq. (8.1)}$$

Thus, the wavelength of sound at 100 Hz is 1,130/100 = 11.3 ft. At 1 kHz, the wavelength is only 1.13 ft. At 10 kHz, the wavelength is 0.113 ft, that is, approximately 1 in. Wavelength is not as commonly used in describing material properties as frequency. However, as Equation (8.1) shows, it is easy to convert from frequency to wavelength and vice versa.

NOTE

Infrasonic, Ultrasonic, and Supersonic

Frequencies below 20 Hz are called *infrasonic* frequencies. They are not heard, but they are perceived by humans as vibrations.

Frequencies above 20 kHz, referred to as *ultrasonic* frequencies, are also not heard by humans.

An object traveling at a speed greater than the speed of sound is said to be traveling at *supersonic* speed.

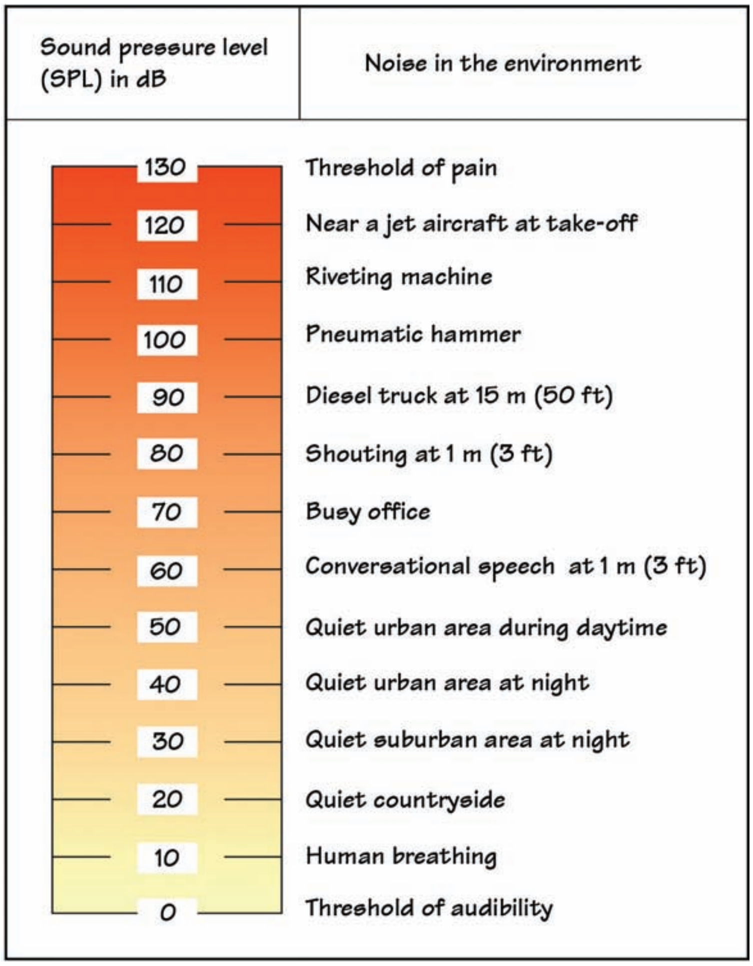
8.2 THE DECIBEL SCALE

The physical quantity associated with the loudness of sound is sound pressure, which can be expressed in pounds per square foot (psf) but is generally expressed in pascals (Pa), a unit in the SI system. The minimum sound pressure to which our ear responds, the *threshold of audibility*, is 0.00002 Pa. The sound pressure that corresponds to the sensation of pain in the ear is approximately 20 Pa (0.4 psf). This is still a very small pressure compared to the atmospheric pressure (101,300 Pa = 2,100 psf) under which we all live.

Although the sound pressures are small, their range is extremely large. Therefore, it is more convenient to use the *decibel* scale in expressing sound pressure. The decibel scale is a logarithmic scale that compares a given sound pressure with the reference sound pressure of 0.00002 Pa, the threshold of audibility.

To distinguish sound pressure (expressed in pascals) from that expressed in decibels, we call the latter the *sound pressure level* (SPL). In other words, the unit for SPL is the decibel (dB). The threshold of audibility is 0 dB, and the threshold of pain is 130 dB. Figure 8.1 gives the approximate SPLs of common environmental sounds.

Obtaining convenient numbers is not the only reason for the use of the decibel scale. The decibel scale also corresponds more directly to the ear's perception of loudness. For instance, a change of 1 dB in SPL is hardly perceived by the human ear. The minimum change in SPL that is just perceptible is 3 dB. A 5-dB change is quite noticeable, and a 10-dB change is perceived as a substantial change.



Sound pressure level (SPL) in dB	Noise in the environment
130	Threshold of pain
120	Near a jet aircraft at take-off
110	Riveting machine
100	Pneumatic hammer
90	Diesel truck at 15 m (50 ft)
80	Shouting at 1 m (3 ft)
70	Busy office
60	Conversational speech at 1 m (3 ft)
50	Quiet urban area during daytime
40	Quiet urban area at night
30	Quiet suburban area at night
20	Quiet countryside
10	Human breathing
0	Threshold of audibility

FIGURE 8.1 Commonly occurring sounds in the environment and their decibel ratings.

8.3 AIRBORNE AND STRUCTURE-BORNE SOUNDS

In building acoustics, we distinguish between two types of sound based on the sound's origin. The reason for the distinction is that building components behave differently with respect to them. The two types of sound are:

- Airborne sound
- Structure-borne sound

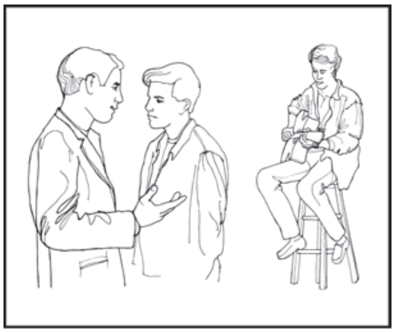


FIGURE 8.2 Examples of airborne sound sources.

Most sounds in buildings are airborne sounds, such as the sounds generated by human conversation and musical instruments, Figure 8.2. Fans, motors, machinery, airplanes, and automobiles are some of the other sources that produce airborne sound.

Structure-borne sound is produced by an impact of some sort on building components—walls, floors, roofs, and so on. The impact causes building elements to vibrate, and as they vibrate, they radiate sound. Because it is impact related, structure-borne sound is also referred to as *impact sound*. Thus, when a nail is driven into a wall or a person walks on a floor, structure-borne sound is produced, Figure 8.3. Other examples of structure-borne sounds are vibrating machinery rigidly connected to a floor, plumbing pipes attached to a wall, and the slamming of a door.

In other words, a structure-borne sound originates in an impact- or vibration-producing source that is in contact with a building component. The building component works as an amplifier of the sound generated by the impact or vibrating source. The impact or vibrating source itself may not create much sound.

For example, a vibrating water tap does not create much sound of its own, but if it is rigidly connected to a wall, its sound is greatly amplified because of the vibrations it produces in the wall. Similarly, the sound produced by a string instrument, such as a guitar, is amplified several fold by the wooden body (sounding board) on which the strings are mounted.

Some sources can produce both airborne and structure-borne sounds. Once the structure-borne sound is produced by a building component, it becomes airborne sound and reaches the receiver as such.

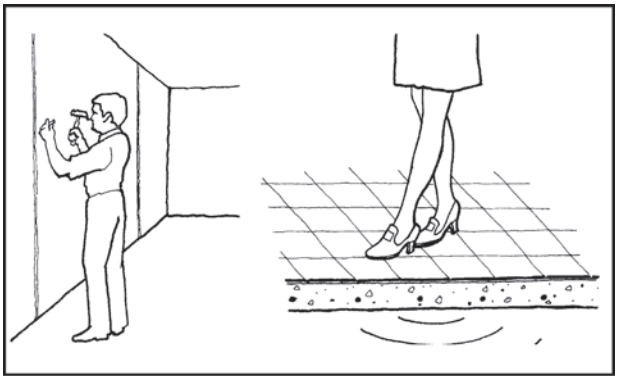


FIGURE 8.3 Examples of structure-borne sound sources.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. Cycles per second is also called a
a. pascal.
b. newton.
c. hertz.
d. hulen.
e. none of the above.

2. Sound that is audible to human beings has a frequency lying between
a. 2 kHz and 20 kHz.
b. 200 Hz and 20 kHz.
c. 100 Hz and 800 Hz.
d. 20 Hz and 20 kHz.
e. 50 Hz and 50 kHz.

3. The pitch of a sound is related to
a. sound frequency.
b. sound energy.
c. sound speed.
d. all of the above.
e. none of the above.

4. Sound speed in air is approximately
a. 10 ft/s.
b. 100 ft/s.
c. 500 ft/s.
d. 1,000 ft/s.
e. 1,100 ft/s.

5. The wavelength of sound at a frequency of 1,000 Hz is approximately
a. 10 ft.
b. 5 ft.
c. 2 ft.
d. 1 ft.
e. 0 ft.

6. The wavelength of sound at a frequency of 100 Hz is approximately
a. 10 ft.
b. 5 ft.
c. 2 ft.
d. 1 ft.
e. 0 ft.

7. The sound created by human speech is
a. airborne sound.
b. structure-borne sound.
c. both (a) and (b).
d. neither (a) nor (b).

8.4 AIRBORNE SOUND INSULATION—SOUND-TRANSMISSION CLASS

When airborne sound energy falls on a building assembly (such as a wall or ceiling), a part of the energy is reflected back into the enclosure, a part of it is absorbed within the material of the assembly and converted to heat, and the remaining part of it is transmitted through it, Figure 8.4. An important property of the building assembly that affects sound reflection, absorption, and transmission is its surface weight (pounds per square foot).

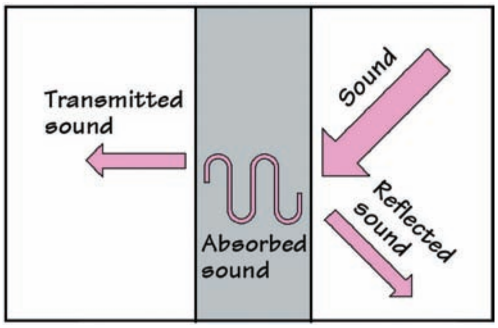


FIGURE 8.4 When a sound falls on a building assembly, a part of it is reflected, a part is absorbed, and the remaining is transmitted through the assembly.

Massive, heavyweight assemblies, such as thick masonry or concrete walls, are good sound insulators because they reflect back most of the sound. Stated differently, heavyweight assemblies are poor transmitters because a relatively small fraction of sound energy goes through them. Conversely, lightweight assemblies, such as stud walls and wood floors, are generally poor sound insulators because a relatively large amount of sound energy goes through them. However, as described later, the sound-insulating properties of lightweight assemblies can be improved by a few special provisions.

The airborne sound insulation of assemblies is measured by a quantity called *sound-transmission loss* (TL). TL is defined as the loss in sound-pressure level that occurs as the sound passes through the assembly. For example, if the sound-pressure level on the source side of a wall is 90 dB and it is 40 dB on the receiver side, the TL of the wall is 50 dB, Figure 8.5. If the sound-pressure level on the source side is 70 dB, then the sound-pressure level on the receiver side of the same wall is 20 dB.

The greater the TL of an assembly, the greater the sound insulation provided by it. An assembly with a TL of 50 dB is a better sound insulator than one with a TL of 40 dB. The TL of an assembly varies with frequency, generally increasing with increasing frequency. In other words, building assemblies generally provide greater sound insulation at high frequencies than at low frequencies.

Because of the variation of TL with frequency, TL cannot be used to compare the sound-insulating efficacy of one assembly with another. For such a comparison, a single-number index is required. This is provided by the quantity called *sound-transmission class* (STC). The STC of an assembly is its average TL over frequencies ranging from 125 Hz to 4 kHz. The greater the STC, the more sound insulating is the assembly. Note that the unit decibel is omitted in quoting the STC value in order to distinguish STC from TL. Thus, we use STC 54, not STC 54 dB, in stating the sound insulation of an assembly. Whole numbers are used in quoting the STC.

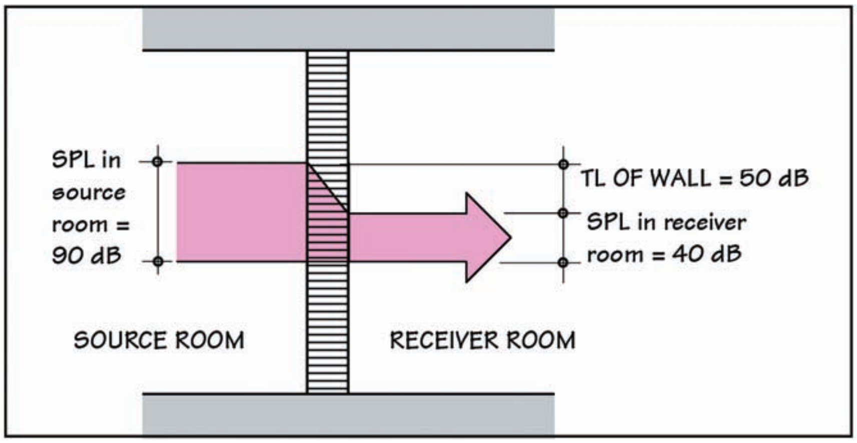


FIGURE 8.5 Definition of the transmission loss (TL) of an assembly.

Subjective Perception of STC Values

STC is an important acoustical index. Manufacturers routinely provide the STC values of their assemblies.

Building codes require that the party wall separating two dwelling units (condominiums or apartments) must have a minimum STC of 50. A higher value is usually required as a good design practice. But how much higher? In other words, how much acoustical privacy does an STC 50 assembly or an STC 55 assembly provide? Table 8.1 attempts to answer these questions. As illustrated in this table, an assembly with an STC of 50 will allow loud speech to be heard through the assembly by a curious listener.

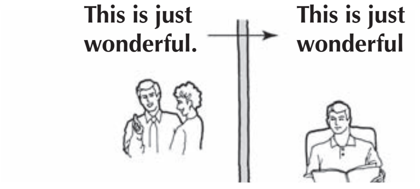
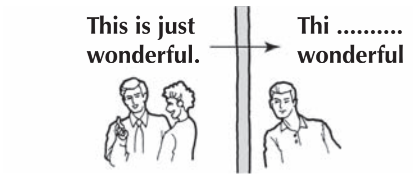
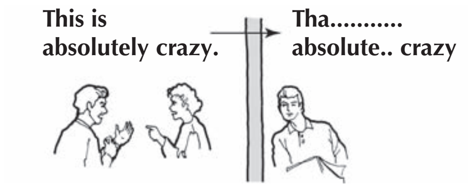
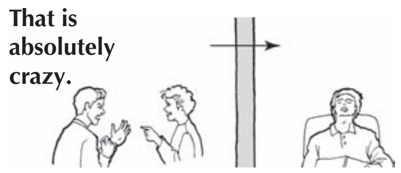
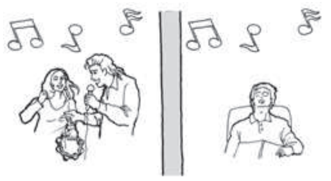
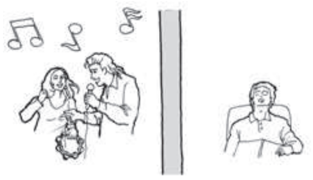
Improving the STC Value of Lightweight Assemblies

As stated earlier, the TL (and hence the STC) of an assembly can be increased if it is made heavier. However, this not only adds to the cost of the assembly but also increases the dead load on the structure. That is why lightweight assemblies, such as steel or wood stud walls lined with gypsum board on both sides, are commonly used.

The STC of a wall with 2 × 4 wood studs and $\frac{1}{2}$-in. gypsum board on each side is only 37. This is an extremely low STC value and, as shown in Table 8.1, provides little acoustical privacy. The following are commonly used methods of increasing the STC of stud-framed walls:

- Add fibrous insulation (e.g., fiberglass or mineral wool) within stud cavities.
- Decouple the gypsum board layer on one side of the assembly from the remaining part of the wall.
- Use multiple gypsum board layers to increase the weight (mass) of the assembly.

TABLE 8.1 SUBJECTIVE PERCEPTION OF STC VALUES

STC	Subjective perception of (acoustical privacy provided by) STC values	
30	 This is just wonderful. This is just wonderful	Most sentences are clearly understood.
40	 This is just wonderful. Thi .... wonderful	Speech can be heard with some effort. Individual words and occasional phrases are heard.
50	 This is absolutely crazy. Tha........... absolute.. crazy	Loud speech can be heard with some effort. Music is easily heard.
60	 That is absolutely crazy.	Loud speech is essentially inaudible. Music is heard faintly; the bass note is disturbing.
70		Loud music is heard faintly, which can be a problem if the adjoining space is highly noise sensitive to sound intrusion, such as a recording studio or a concert hall.
75 and above		Most noises are effectively blocked.

This table assumes a reasonably quiet environment in the receiving room.

TABLE 8.2 APPROXIMATE STC VALUES OF SELECTED WOOD STUD ASSEMBLIES WITH $\frac{1}{2}$-IN.-THICK GYPSUM BOARD ON BOTH SIDES OF STUDS

	Without cavity absorption Layers of gypsum board			With cavity absorption Layers of gypsum board		
Gypsum board support system	**1 + 1**	**1 + 2**	**2 + 2**	**1 + 1**	**1 + 2**	**2 + 2**
2 × 4 wood studs	37	40	43	40	43	46
2 × 4 wood studs, resilient channel (or clip) on one side	40	45	49	50	53	57
2 × 4 wood studs, resilient channel (or clip) on both sides	41	46	51	49	53	58
2 × 4 wood stud wall (staggered studs)	41	48	52	50	54	58
Double-stud wall with 1-in. space between studs	46	53	57	57	61	63

As shown in this table, using a resilient channel (or clip) on one side of a wall is adequate. Using the channel (or clip) on both sides of the wall gives a negligible increase in STC value.

Fibrous insulation helps to retard the vibration of air within the wall cavity, thereby absorbing the sound. Decoupling reduces the transfer of vibrations from one side of the wall to the other. Using multiple gypsum board layers increases the surface weight of the wall. Table 8.2 shows the STC values of a few selected lightweight assemblies.

Decoupling is one of the most effective means of increasing the STC of a lightweight wall. It is achieved by using either a staggered-stud wall or a double-stud wall assembly, Figures 8.6 and 8.7. The STC value of a staggered-stud wall is lower than that of a double-stud wall because the staggered-stud wall is not fully decoupled due to the presence of common top and bottom plates.

RESILIENT CHANNELS AND RESILIENT CLIPS

A more commonly used means of decoupling is to use a resilient channel or a resilient clip. A resilient channel is a light-gauge steel member, Figure 8.8 (see also Figure 20.9). Resilient channels are fastened to studs (typically at 24-in. center), and the gypsum board is fastened to the resilient channels.

In fastening the resilient channel, its free end must be toward the top, so that when the gypsum board is fastened, the free end pulls away from the studs. If the free end is toward the bottom, decoupling will not be achieved.

A resilient clip is a more recently introduced device as an alternative to the resilient channel. It consists of a light-gauge steel clip with a rubber pad, Figure 8.9. The rubber pad functions as a vibration absorber.

IMPORTANCE OF AIR SEALS FOR AIRBORNE SOUND INSULATION

Because sound travels through the air, it is important that an assembly contain no voids if it is required to have a high STC. Remember that if air can go through the assembly, so will sound. It is futile to increase the surface weight of the assembly or use resilient channels,

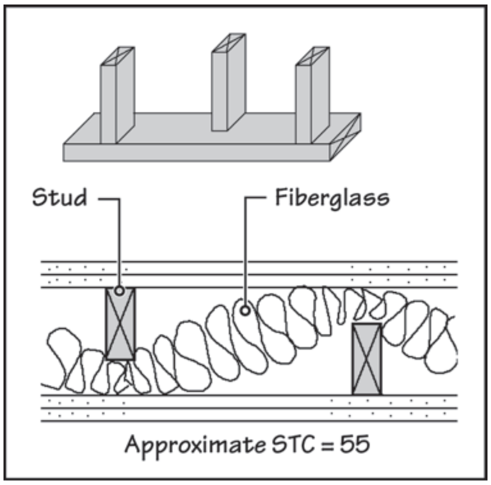


FIGURE 8.6 Staggered-stud wall assembly with cavity absorption (fiberglass or mineral wool).

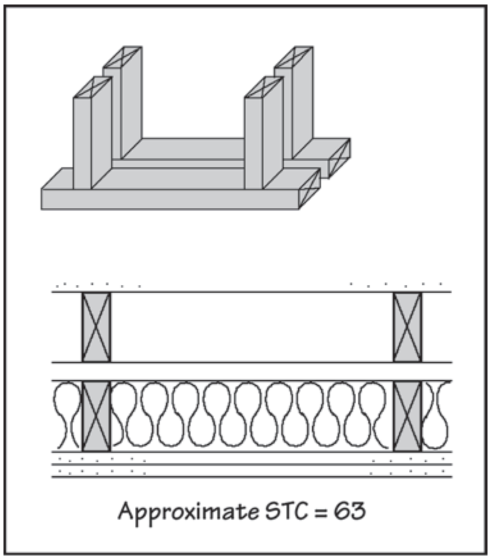


FIGURE 8.7 Double-stud wall assembly.

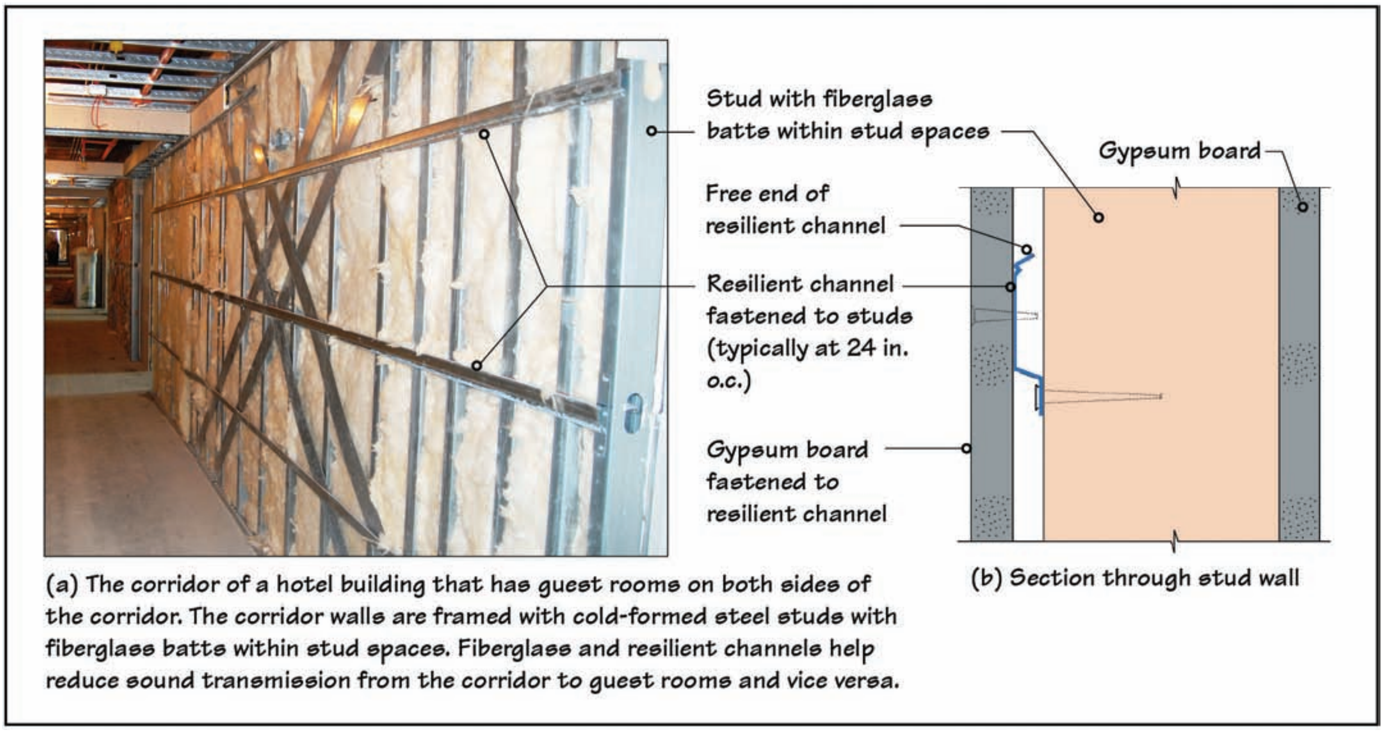

Stud with fiberglass batts within stud spaces
Gypsum board
Free end of resilient channel
Resilient channel fastened to studs (typically at 24 in. o.c.)
Gypsum board fastened to resilient channel
(a) The corridor of a hotel building that has guest rooms on both sides of the corridor. The corridor walls are framed with cold-formed steel studs with fiberglass batts within stud spaces. Fiberglass and resilient channels help reduce sound transmission from the corridor to guest rooms and vice versa.
(b) Section through stud wall

FIGURE 8.8 Resilient channel and its profile. Resilient channels are used to reduce airborne sound transmission through walls and ceilings.

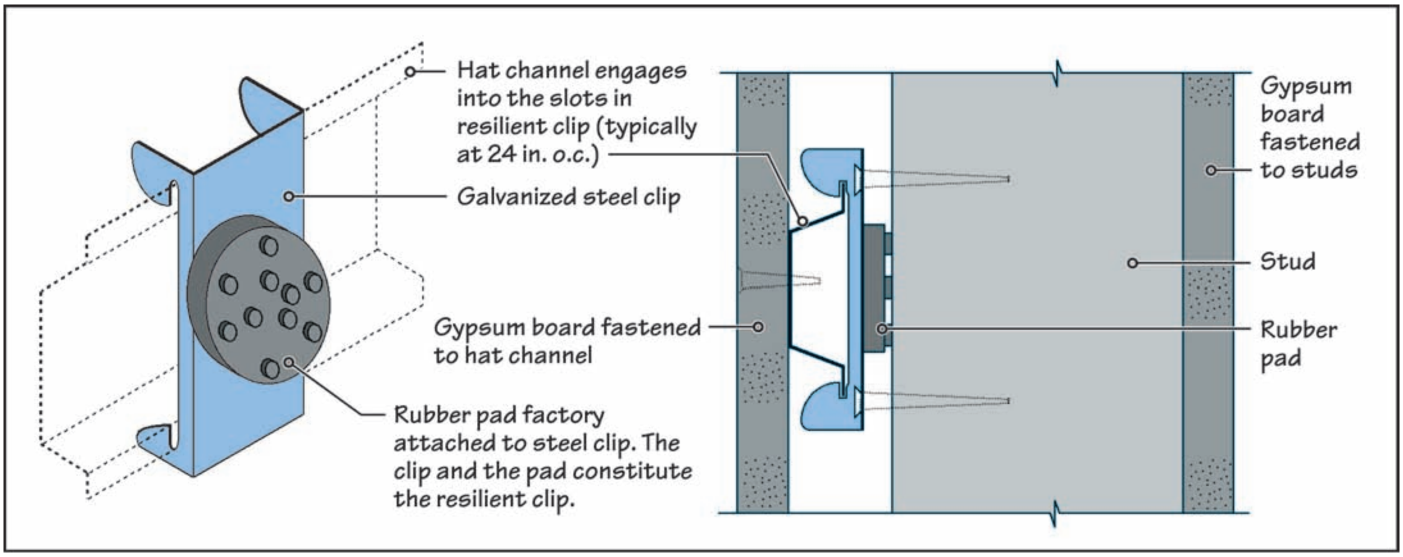

Hat channel engages into the slots in resilient clip (typically at 24 in. o.c.)
Galvanized steel clip
Gypsum board fastened to hat channel
Rubber pad factory attached to steel clip. The clip and the pad constitute the resilient clip.
Gypsum board fastened to studs
Stud
Rubber pad

FIGURE 8.9 Resilient clip and its use.

clips, or staggered studs if air can leak through the assembly. Therefore, the assembly should be fully sealed at all edges (perimeter) and contain no air-leakage sites.

8.5 STRUCTURE-BORNE SOUND INSULATION—IMPACT INSULATION CLASS

An effective way to reduce structure-borne sound transmission is to reduce the vibrations at the source (before they become structure-borne) by absorbing them through the use of resilient materials. For example, the most common structure-borne sound in buildings is produced by the floors as a result of footsteps, furniture movement, or the vibration of machinery supported by the floor. The best way of reducing the transmission of this sound through the floor is to dampen the impact through a soft covering over the floor.

The measure used to quantify structure-borne sound insulation is *impact insulation class* (IIC). As with STC values, the unit decibel is not used with IIC values.

A soft covering, such as carpet backed by a foam underlayment, increases the IIC substantially. For example, the IIC of a bare 6-in.-thick concrete floor is 25. The same floor covered with a carpet and underlayment gives an IIC of 85—an increase of 60. Note that a carpet does not improve the STC of a floor. The STC of a 6-in.-thick concrete slab is 55, regardless of whether the floor is bare or covered with a carpet.

The improvement in the IIC of wood floors by using a carpet is less pronounced because of the inherent resilience of a wood floor. For example, a typical plywood floor on wood joists and a gypsum board ceiling directly attached to the studs has an IIC of 34 without the carpet and 55 with the carpet, Figure 8.10. Building codes require a minimum IIC of 50 for a floor-ceiling assembly between two independent dwelling units, such as in an apartment building.

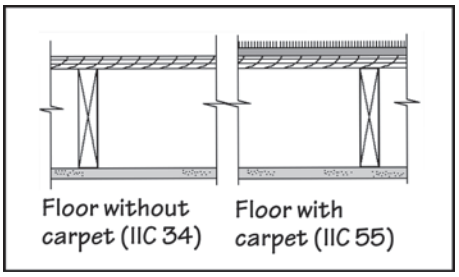


FIGURE 8.10 IIC of a wood floor without and with carpet and underlayment.

8.6 SOUND ABSORPTION—NOISE-REDUCTION COEFFICIENT

While the sound originating from outside a receiving room is attenuated (reduced) by using sound-insulating construction, that originating from within the room can be reduced only by using sound-absorbing materials. All materials and objects absorb sound to some degree. However, materials whose sound-absorption coefficient is greater than 0.2 are called *sound-absorbing materials*, or *acoustical materials*, although the former term is preferable. For the same reason, the term *acoustical treatment* usually implies sound-absorptive treatment.

The sound-absorption coefficient of an assembly, α, is defined as the sound energy that is not reflected by the assembly divided by the total sound energy falling on the assembly. The term *not reflected* is used because it includes both the absorbed energy and the energy transmitted through the assembly. From the point of view of an enclosure, an open window is considered to be a perfect acoustical absorber because it does not reflect any sound.

The value of α lies between 0 and 1 and varies with the frequency of sound. For most sound-absorbing materials, we are concerned with the value of α for frequencies between 250 Hz and 2 kHz because, as noted earlier, it is the frequency range of human speech.

Because of its variation with frequency, we cannot use the value of α to compare the sound-absorbing efficacy of one material with another. Therefore, we use a single-number metric called the *noise-reduction coefficient* (NRC), which is the value of α for a material averaged over the frequency range of 250 Hz to 2 kHz. Because NRC is the average value of α, NRC also lies between 0 and 1. The higher the NRC, the more sound absorptive is the material.

The most commonly used materials for sound absorption are porous materials, called *porous sound absorbers*. They absorb sound because the air particles in the vicinity of the material go back and forth into the pores and convert their vibrational energy into heat through friction. Because the energy contained in sound is extremely small, the amount of heat so created is negligible.

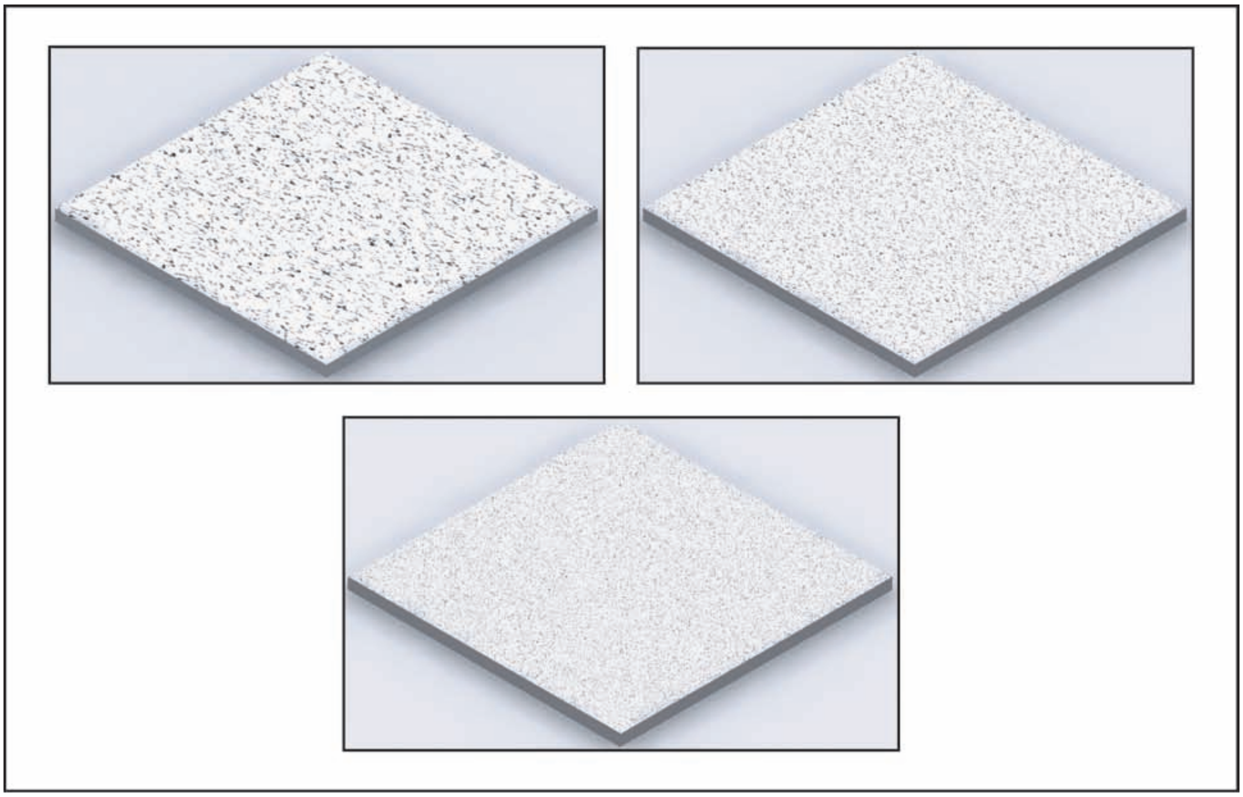


FIGURE 8.11 Various types of perforations used in ceiling tiles made from mineral fiberboard (see Chapter 37).

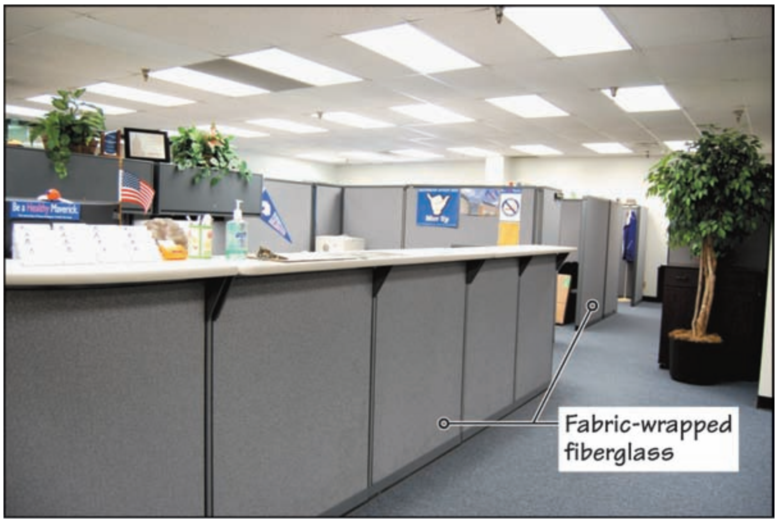


FIGURE 8.12 Low-height partitions in a large open-plan office are usually made of fabric-wrapped fiberglass to provide sound absorption, reducing the ambient noise level.

For a porous material to be a good sound absorber, it is important that it has interconnected pores. Plastic foams (such as extruded polystyrene, polyisocyanurate, and so on), used as thermal insulators, are not good sound absorbers because their pores are not interconnected. Fiberglass, rock wool, slag wool, and other mineral fibers are the most commonly used sound-absorbing materials because they have interconnected pores and also because they are noncombustible.

The NRC value of a porous sound absorber is a function of its thickness. A thicker porous absorber generally has a higher value of NRC. Manufacturers routinely quote the NRC value for their sound-absorptive materials. A commonly used porous absorber is the ceiling *tile*, generally a mineral fiberboard product, in which the perforations can take various patterns, Figure 8.11. Other materials, particularly fiberglass wrapped in a perforated fabric, is commonly used to absorb sound, thereby reducing ambient noise levels. Figure 8.12 is an example of low-height partitions in an open-plan office faced with fabric-wrapped fiberglass.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

8. Compared to a lightweight building element, a heavyweight element is generally a poor transmitter of airborne sound.
- **a.** True
- **b.** False

9. Most of the noise produced in a busy restaurant or dining hall is
- **a.** airborne sound.
- **b.** structure-borne sound.

10. Sound transmission class (STC) is a measure of the
- **a.** sound-absorbing property of a material.
- **b.** sound-insulating property of a material with respect to airborne sound.
- **c.** sound-insulating property of a material with respect to structure-borne sound.
- **d.** sound-reflecting property of a material.

11. For a party wall between two dwelling units, such as two apartments, the building codes require its minimum STC value to be
- **a.** 100.
- **b.** 75.
- **c.** 65.
- **d.** 55.
- **e.** 50.

12. A resilient clip consists of a small light-gauge steel member with a rubber pad fastened to it.
- **a.** True
- **b.** False

13. A resilient channel is used to attenuate airborne sound, whereas a resilient clip is used to attenuate structure-borne sound.
- **a.** True
- **b.** False

14. A sound barrier with an STC of 50 will generally
- **a.** block all speech and music, however loud.
- **b.** block loud speech but not loud music.
- **c.** block loud music but not loud speech.
- **d.** not block music but will block speech sufficiently to be heard only by a curious listener.

15. The measure that is used for structure-borne sound insulation is
- **a.** transmission loss.
- **b.** impact isolation index.
- **c.** impact insulation class.
- **d.** structural insulation index.

16. A commonly used porous sound absorber is
- **a.** gypsum board.
- **b.** aluminum foil.
- **c.** microperforated plastic.
- **d.** oriented strandboard.
- **e.** fiberglass.

17. The noise-reduction coefficient (NRC) of a material is evaluated between the frequency range of 250 Hz and 2 kHz because
- **a.** it is virtually impossible to evaluate this property outside the above frequency range.
- **b.** the human ear is insensitive to noise outside the above frequency range.
- **c.** most of the sound energy in the noise produced in buildings lies in the given frequency range.
- **d.** most of the sound energy in human speech lies in the given frequency range.
- **e.** none of the above.

18. The NRC of a material lies between
- **a.** 0 and 100.
- **b.** 1 and 100.
- **c.** 0 and 10.
- **d.** 1 and 10.
- **e.** none of the above.

CHAPTER 9

Principles of Joints and Sealants (Expansion and Contraction Control)

CHAPTER OUTLINE

9.1 Types of Movement Joints

9.2 Building Separation Joints and Seismic Joints

9.3 Movement Joints in Building Components

9.4 Thermal Movement

9.5 Moisture Movement

9.6 Elastic Deformation and Creep

9.7 Total Joint Dimension

9.8 Principles of Joint Detailing

9.9 Components of a Sealed Joint

9.10 Types and Properties of Joint Sealants

Building joints result from our need to work with materials that can be easily and efficiently fabricated, transported, and assembled on site. The joints also allow field adjustments in assemblies during construction. Additionally, visible connections resulting from the joints provide the opportunity to develop ideas of scale, pattern, color, texture, and so on, on building planes and surfaces, Figure 9.1.

The most important issue in the design of building joints is that the dimensions of building components are constantly changing, not only with respect to their original dimensions, but also relative to each other. For example, window glass expands and contracts in response to external temperature changes. The changes in glass dimensions are usually different from the corresponding changes in the frames that hold the glass. Yet we still need to be able to make a secure connection between the window glass and the frame.

Static Joints and Movement Joints

Over the years, two different strategies have been developed for joining building components. We could provide a nonmoving joint (connection) between the components, called a *static joint*. In the case of the window glass and frame, a static joint would most likely result in broken glass, a broken frame, or both. The alternative is to provide a connection that allows both materials to move independently and at the same time hold the window glass securely in the frame. This movable connection is called a *dynamic joint* or, more commonly, a *movement joint*.

Static joints typically connect materials that are the same or similar. For instance, the mortar joints between units of masonry, the joint between two sheets of gypsum board, and most structural joints provide nonmoving connections between components. By their

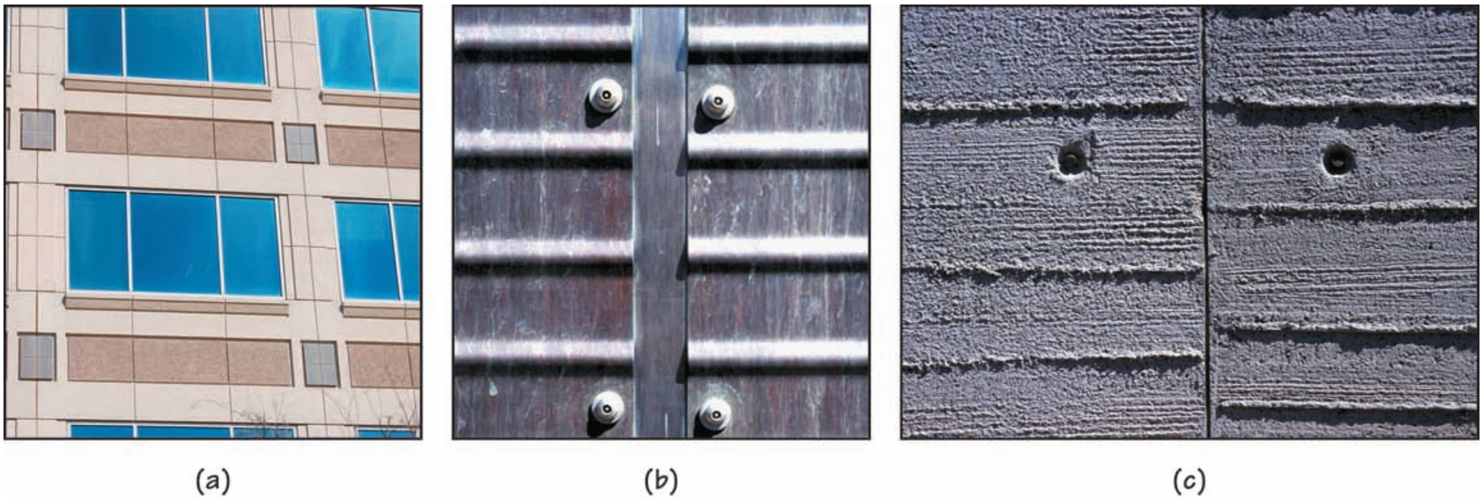

(a) (b) (c)

FIGURE 9.1 **(a)** Joints are a common feature in buildings, particularly on building facades. Some of these joints are aesthetic joints to provide surface relief, rhythm, patterns, and so on, while others are provided for performance reasons related to building design and (or) construction. **(b)** The fasteners used in the joint in the copper cladding of Burton Barr Central Library, Phoenix, Arizona, contribute to the rhythm and pattern in the cladding. **(c)** The textured surface and the bold horizontal lines in the exterior concrete walls of the same library building relieve the monotony of a large concrete surface.

nature, the movement of components in a static joint is restricted, so the stress created by such restraint must be counteracted by increased strength of the components.

A well-designed movement joint, on the other hand, has no movement stress. Therefore, it is used at the connection of materials that move at different rates. This implies that movement joints are placed where dissimilar materials meet. They may also be needed to subdivide a component into smaller sizes in order to reduce internal stresses. It is for this reason that a concrete slab-on-grade is subdivided into smaller areas with a gridwork of joints. It is also the reason that a masonry wall—an assembly of static (mortar) joints—must be provided with movement joints at intervals.

The focus of this chapter is on movement joints. Because a movement joint is generally required to be sealed against air, water, and noise transmission (particularly the joints that occur in the external envelope of the building), we will also examine the commonly used sealants and sealant backup materials. Issues related to preventing movement of rainwater through wall assemblies and their joints are discussed specifically in Chapter 27.

NOTE

Construction Joint

A special type of static joint that is provided between two concrete placements is called a *construction joint* or *cold joint* (Chapter 22).

9.1 TYPES OF MOVEMENT JOINTS

Based on the purpose they serve, movement joints are classified as:

- *Building joints*—joints between different parts of the building as a whole
- *Component joints*—joints between individual components of an assembly

A building joint divides the entire building into two or more separate buildings. Based on the purpose for which it is provided, it is classified as either a *building separation joint* or a *seismic joint*.

A joint between two adjacent building components can be an *expansion joint*, a contraction joint (commonly called a *control joint*), or an *isolation joint*. A complete list of movement joint types in a building is given in Figure 9.2. Joint types are discussed in detail in the following sections.

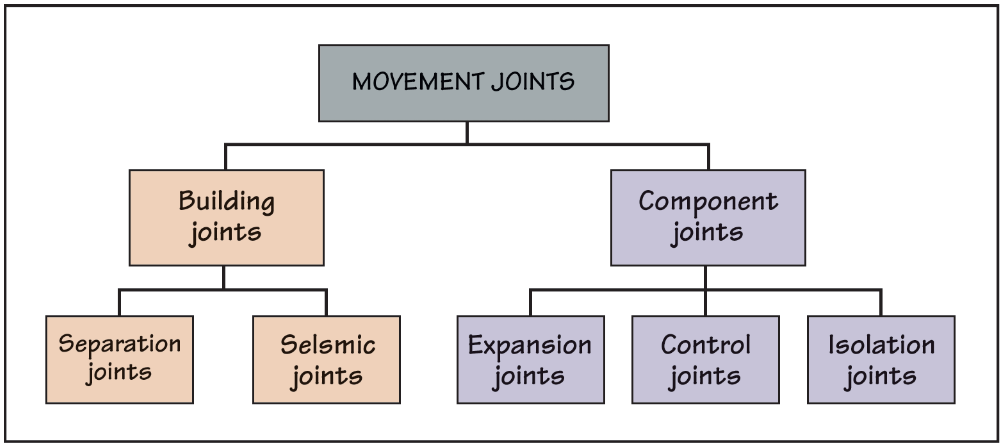


FIGURE 9.2 Types of movement joints in a building.

9.2 BUILDING SEPARATION JOINTS AND SEISMIC JOINTS

A building separation joint runs continuously throughout the entire building from floor to floor and from face to face. It divides a large and geometrically complex building into smaller, individual, and geometrically simplified buildings, which can move independent of each other. This joint, typically 1.5 to 2 in. wide, accommodates the cumulative effect of various types of movements that occur in a building as a whole, as distinct from the movements that occur in individual components of the building.

A building separation joint prevents the stresses created in one part of the building from affecting the integrity of the other part. A building separation joint is needed in large buildings. As a rough guide, it should be provided at 250-ft (75-m) intervals, Figure 9.3. In addition, good practice requires the provision of building separation joints at the following discontinuities:

- Where a low building mass meets a tall mass. This prevents problems caused by differential expansion and contraction (including creep), in addition to any differential settlement of foundations. Minor changes in height should be disregarded.
- Where the building changes direction, such as in an L-shaped or T-shaped building. Minor changes in direction should be ignored.
- Where the building's structural material changes, such as where a steel frame building meets a concrete frame. This prevents problems due to differential movement between disparate structural systems.

As far as possible, a building separation joint should divide a large building into separate smaller buildings of simplified geometries, such as rectangles. The division into separate buildings requires the use of two columns and two beams at a building separation joint, Figures 9.4 to 9.6.

The duplication of columns and beams at a building separation joint is an ideal solution. An alternative solution that is commonly used is shown in Figures 9.7 and 9.8, in which a single column with a bracket is used.

SEISMIC JOINT

A seismic joint is similar to but also different from a building separation joint. Building separation joints are introduced to accommodate moderate building movements caused by temperature and moisture changes, creep, and foundation settlements. Although they can accommodate small vertical movement, they are designed to accommodate mainly horizontal movement, that is, in the direction perpendicular to the joint.

NOTE

Building Separation Joint (or Building Expansion Joint)

The term *building expansion joint* is often used for building separation joint in some literature. This is not entirely correct, because a building separation joint accommodates more than mere expansion and contraction of a building.

NOTE

Spacing Between Building Separation Joints

The suggested spacing of 250 ft between building separation joints should be regarded as a rough guide. Most buildings of a simple rectangular shape up to 300 ft in length do not need separation joints. On the other hand, a building with major deviations from a rectangular shape may need separation joints at less than 250 ft on center.

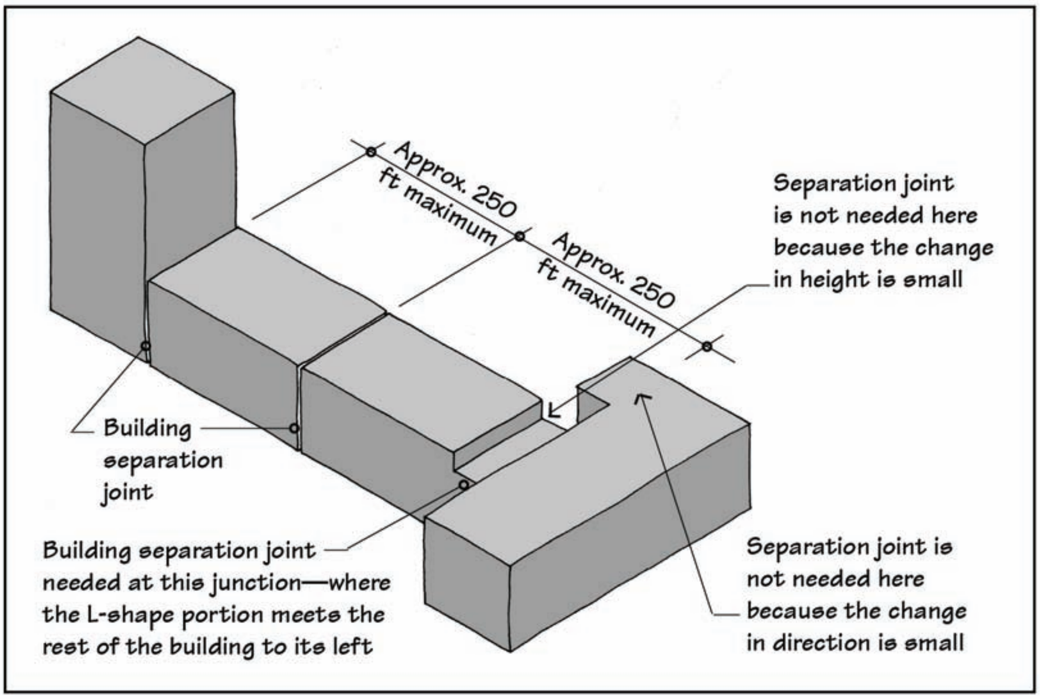

Approx. 250 ft maximum
Approx. 250 ft maximum
Separation joint is not needed here because the change in height is small
Building separation joint
Building separation joint needed at this junction—where the L-shape portion meets the rest of the building to its left
Separation joint is not needed here because the change in direction is small

FIGURE 9.3 A building separation joint should divide the building into smaller, structurally independent sections (as if they are separate buildings) so that each section is geometrically simple.

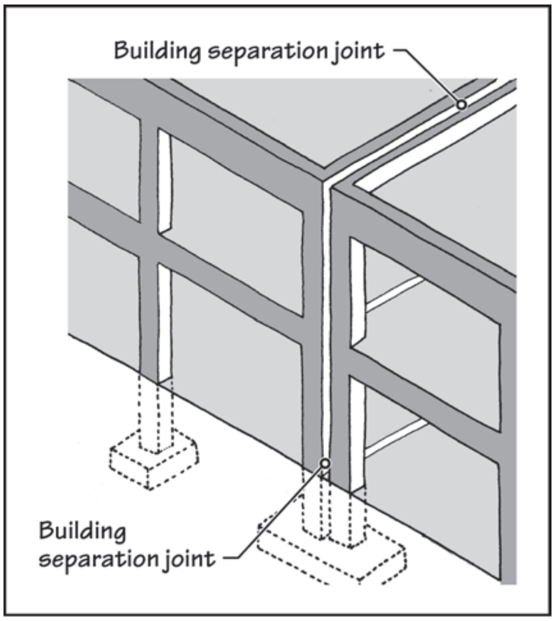

Building separation joint
Building separation joint

FIGURE 9.4 A building separation joint runs through the entire building from the ground floor (or the basement, if provided) up to the roof. Two columns are often used at the separation joint. However, a combined footing may be used for the two adjacent columns.

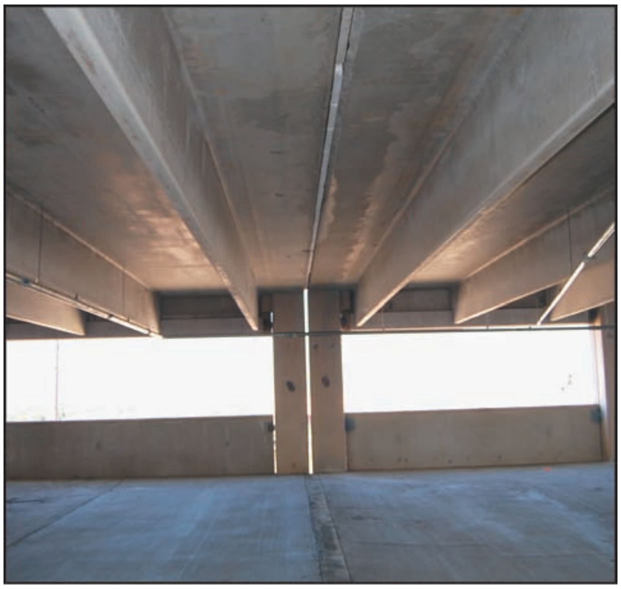
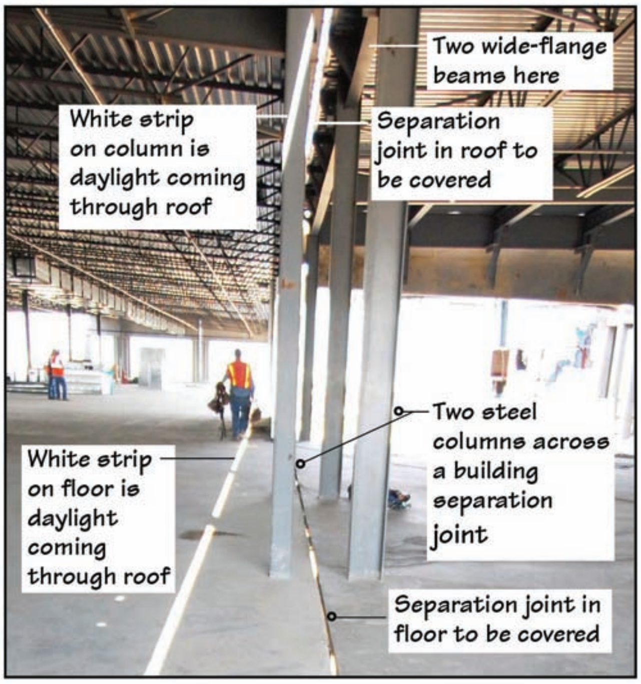


FIGURE 9.5 Building separation joint with two columns in a reinforced concrete building. Because the building is under construction, daylight is showing through the joint between the columns. In a completed building, the joint is sealed and covered with a joint cover, as is the case here for the separation joint in the floor.

FIGURE 9.6 Building separation joint with two columns and two beams in a steel frame building. Because the building is under construction, daylight is showing through the separation joint at the roof level. In a completed building, the joints at the floor and roof levels will be suitably covered. Note that because a separation joint separates a building into two independent buildings, the columns on each side of a separation joint need not align, that is, they can be offset from each other, as seen in the photograph.


Two wide-flange beams here
White strip on column is daylight coming through roof
Separation joint in roof to be covered
Two steel columns across a building separation joint
White strip on floor is daylight coming through roof
Separation joint in floor to be covered

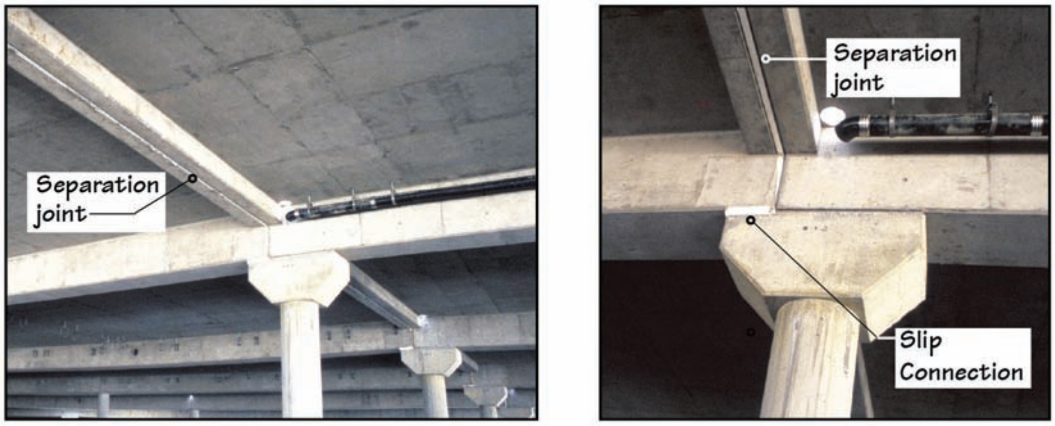

Separation joint
Separation joint
Slip Connection

FIGURE 9.7 Building separation joint using a single column in a reinforced concrete building (see Expand Your Knowledge in Chapter 23 for details). Observe the provision of a beam on each side of the separation joint.

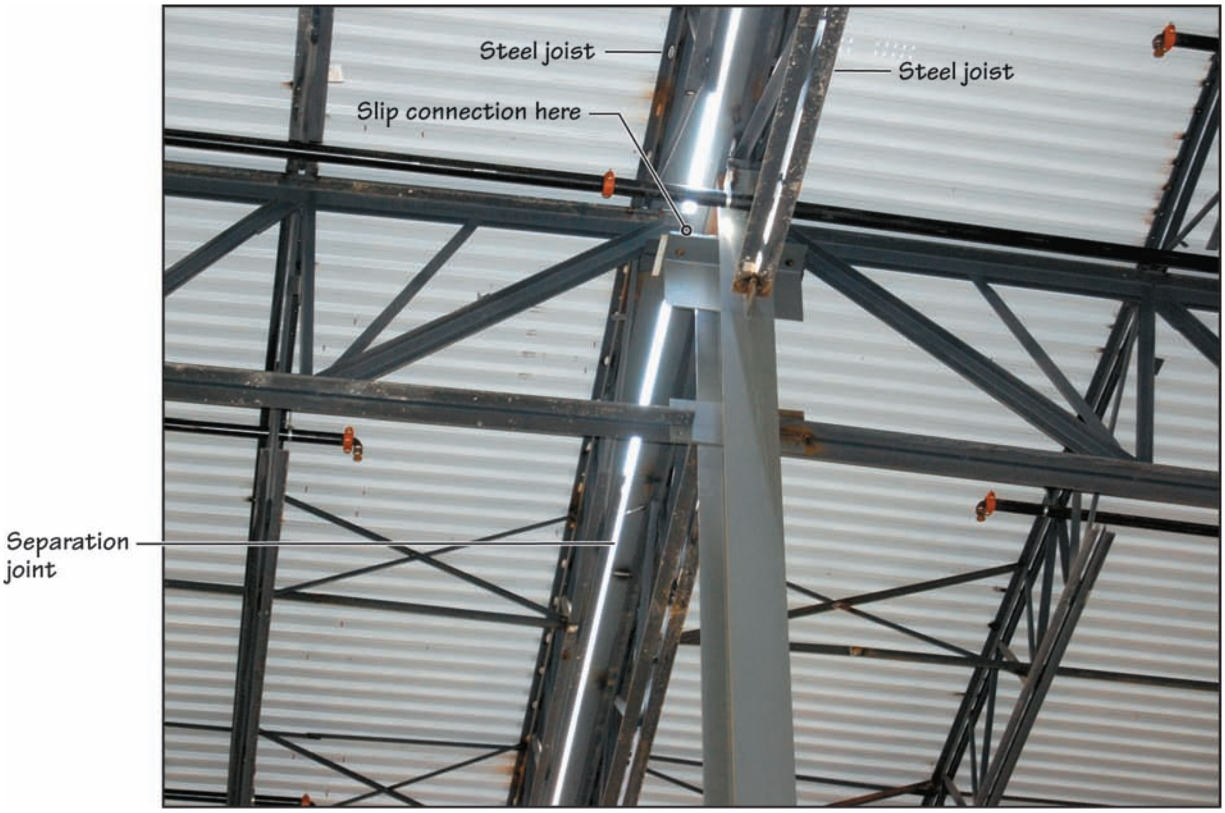

Steel joist
Steel joist
Slip connection here
Separation joint

FIGURE 9.8 Building separation joint in a steel frame building using a single column. Because the building is under construction, daylight is showing through the separation joint. In a completed building, the joint is sealed and covered with a joint cover (see Chapter 19 for details of the separation joint). Observe the provision of a steel joist on each side of the separation joint.

Like building separation joints, seismic joints are also provided where there are major dissimilarities in building form. However, the purpose of seismic joints is to ensure that one section of the building does not collide with the adjacent section during an earthquake. A seismic joint must accommodate simultaneous movements in horizontal as well as vertical directions, that is, in all three principal directions.

A seismic joint is generally much wider than a building separation joint. In highly seismic locations, a seismic joint may be a few feet wide for a tall building. The width of a building separation joint is the same at each floor. The width of a seismic joint, on the other hand, should increase with height. For aesthetic and architectural reasons, however, a constant width is generally used.

Using double columns at a seismic joint is the preferred solution. However, a single column with seated connections (Figures 9.7 and 9.8) that are adequately restrained to prevent the seat from sliding off the support is acceptable.

COVERS OVER BUILDING SEPARATION OR SEISMIC JOINTS

Building separation and seismic joints must be covered. Various proprietary products are available to cover the joints at the roof, floors, and walls. A simple floor joint cover consists of a compressible gasket between two metal sections. Each metal section is anchored to the floor slab, Figure 9.9.

A more elaborate floor joint cover that allows greater movement is used for seismic joints. It is important to ensure that the joint has the same fire resistance as the floor, wall, or roof in which it occurs. Once again, proprietary fire-resistive joint materials (typically consisting of ceramic insulation encapsulated

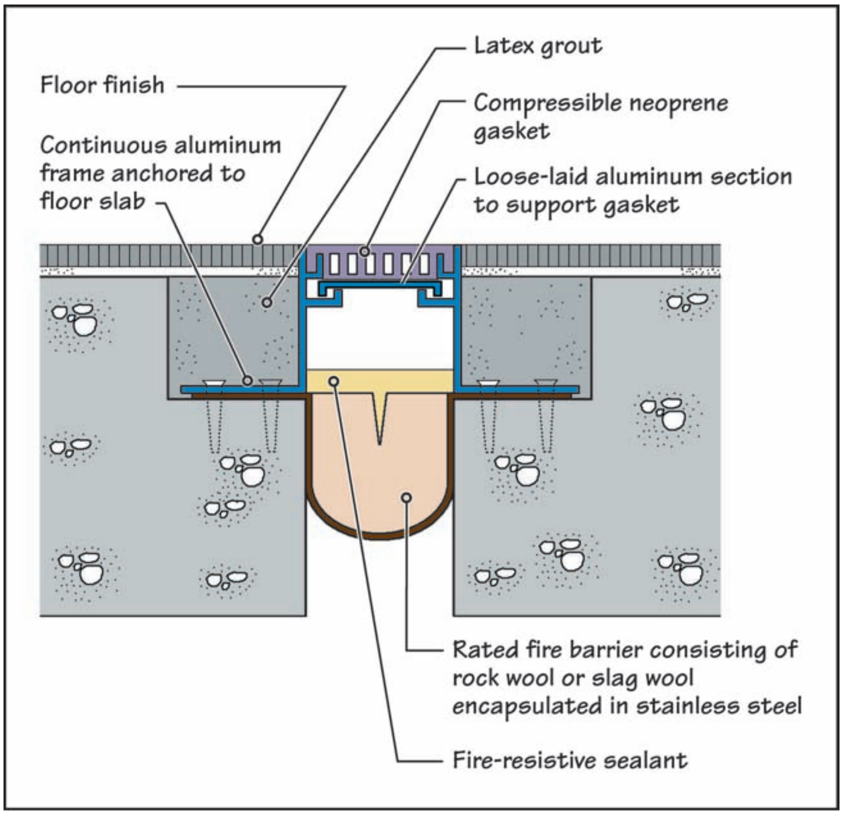

Latex grout
Floor finish
Compressible neoprene gasket
Continuous aluminum frame anchored to floor slab
Loose-laid aluminum section to support gasket
Rated fire barrier consisting of rock wool or slag wool encapsulated in stainless steel
Fire-resistive sealant

FIGURE 9.9 A typical detail of a building separation joint cover at the floor level. Similar covers are provided in interior and exterior walls and roofs. Joint cover manufacturers' details and specifications should be strictly followed for structural, fire rating, and other performance reasons.

in a stainless steel sheet) are available to use within the joint. Building separation joints at the roof are discussed in Chapter 33.

9.3 MOVEMENT JOINTS IN BUILDING COMPONENTS

Movement in a building component can be caused by several phenomena. Therefore, many factors must be considered in sizing and detailing movement joints in building components:

- Thermal movement
- Moisture movement
- Elastic deformation and creep
- Construction tolerances and other considerations

Although thermal movement and elastic deformation occur in all materials, the same is not true of creep and moisture movement. Steel does not creep, and its dimensions are not affected by moisture variations. Thermal movement is reversible if the component is unrestrained. Moisture movement, on the other hand, may or may not be reversible, depending on the material, Table 9.1. Creep deformation is irreversible; that is, creep is a permanent deformation.

In addition to the factors just stated, construction and material tolerances and several other factors must be considered in sizing building component joints.

Because of the multiplicity of factors and their intricate interrelationships, the theory of sizing movement joints can be fairly complex. Therefore, in practice, joint dimensions are based on well-acknowledged rules of thumb. In most situations, the rules of thumb are established by material manufacturing associations. For instance, the Brick Industry Association (BIA) provides rules of thumb for the size and spacing of joints in brick walls. Similarly, the Portland Cement Association (PCA) and the American Concrete Institute (ACI) provide rules of thumb for joints in concrete slabs and walls.

TABLE 9.1 TYPES OF MOVEMENT IN SELECTED MATERIALS

Building material	Thermal	Elastic deformation	Creep	Reversible moisture	Irreversible moisture
Steel	X	X	—	—	—
Concrete	X	X	X	X	—
Concrete masonry	X	X	X	X	—
Brick masonry	X	X	X	—	X
Wood	X	X	X	X	—

X indicates the presence of particular movement in the material and—indicates the absence of such movement.

EXPAND YOUR KNOWLEDGE

Importance of Movement Joints in Building Components

The importance of providing an adequate space for the movement of components may be appreciated by considering the expansion of a linear member such as a beam. Assume that the original length of a beam is L. Assume further that, under certain temperature and moisture changes, its length increases by an amount δ. If the beam is fully restrained at its ends so that it cannot increase in length, it will be subjected to axial compression. Consequently, the beam will tend to buckle (bend upward or downward), Figure 9.10. If the deflection of the beam is denoted by h, we find that h is several times larger than the beam's unrestrained extension, δ.

To better visualize this fact, consider the following illustrative scale model. An approximately 4-ft-long sheet made of a flexible material (e.g., acrylic) has been cut to fit snugly between two raised ends, Figure 9.11(a). The raised ends restrain the expansion of the sheet. If we slightly shorten the length of the sheet (say, by approximately $\frac{1}{16}$ in.) on each end by placing a 25-cent

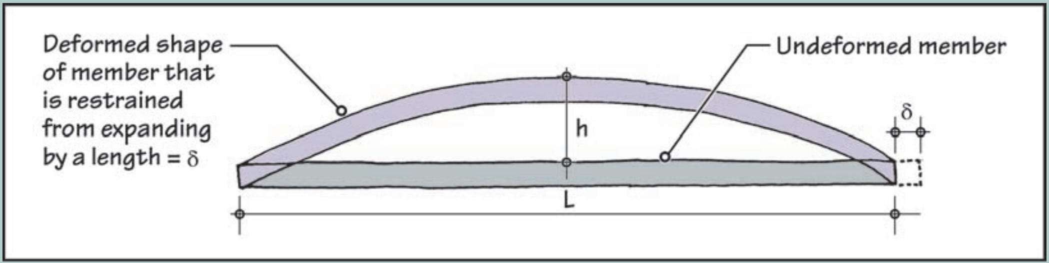

Deformed shape of member that is restrained from expanding by a length = δ
Undeformed member
h
δ
L

FIGURE 9.10 Deformation of a member that is prevented from expanding. Note that restraint against even a small expansion (δ) can cause a large lateral deformation (h) in the member.

EXPAND YOUR KNOWLEDGE

coin between the sheet and the raised end, we find that the sheet curves up substantially (approximately 2 in.), Figure 9.11(b).

Apart from the fact that such a large deformation is visually unacceptable in buildings, it also creates structural problems. A component made of a ductile material (e.g., metal or plastic) will buckle in such a situation. On the other hand, materials such as concrete, masonry, gypsum drywall, and glass will simply break under such a large deformation because, being weak in tension, these (brittle) materials cannot resist the tensile stress created by excessive bending.

This simple model highlights the importance of providing movement joints. A similar situation would occur if the beam were to contract instead of expanding. Contraction creates axial tensions, and most brittle materials will fail under relatively small contraction because their tensile strength is low.

If the component is free to move due to the provision of movement joints, no stress will be created in the component. However, although movement joints provide a convenient solution to expansion and contraction, they can be avoided (where the situation so requires) by increasing the strength and stiffness of the component. For example, the buckling of the acrylic sheet in Figure 9.11(b) can be prevented by increasing the strength (i.e., thickness) of the sheet or replacing it by a stiffer material.

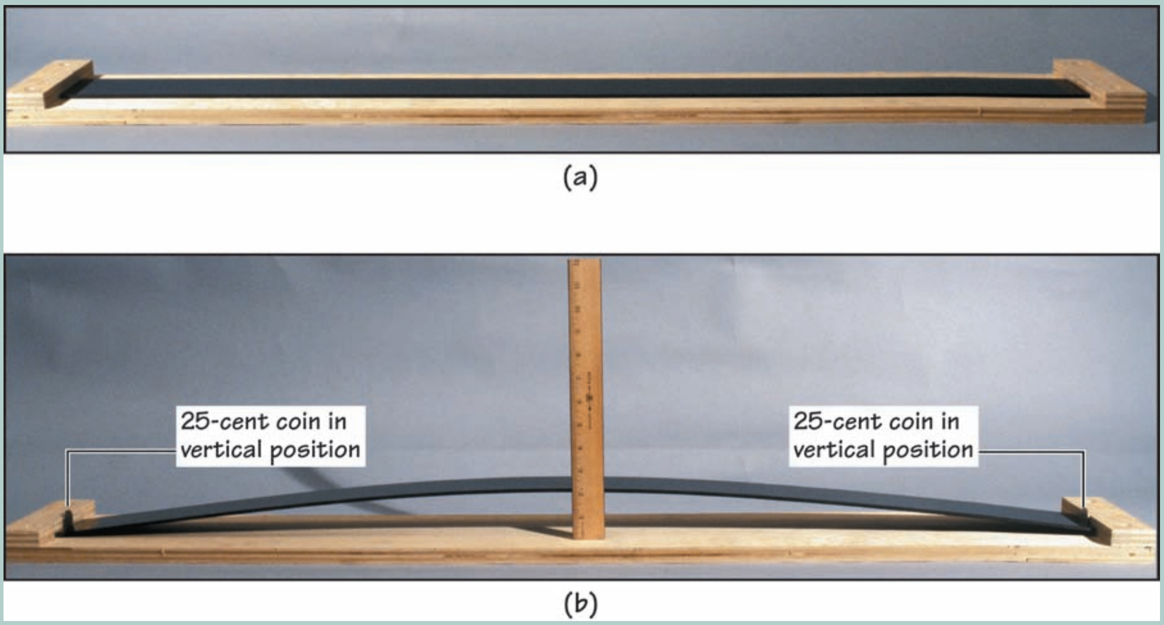

(a)
25-cent coin in vertical position
25-cent coin in vertical position
(b)

FIGURE 9.11 **(a)** An acrylic sheet in an undeformed state. **(b)** Deformation of the same sheet (nearly 4 ft long) shortened by approximately $\frac{1}{16}$ in. at each end by placing 25-cent coins. Note that the (lateral) deformation of the sheet (approximately 2 in.) is much larger than the longitudinal shortening (approximately $\frac{1}{8}$ in.).

Despite the general use of rules of thumb, a basic understanding of the theory of movement of building components is important and is presented in the following sections. This information is critical when the designer must depart from the rules of thumb. It is also important in situations where rules of thumb do not exist.

9.4 THERMAL MOVEMENT

Thermal movement is generally the most critical movement because it occurs in all components, particularly those exposed to the exterior climate, such as exterior walls, cladding, roof membranes, slabs, and paving. It is also the largest type of movement in most components.

To determine the thermal expansion or contraction of a component, assume that its length is L and the temperature change it experiences is Δt (°F or °C). If the component is not restrained, its length will increase (or decrease) so that the new length will be $(L + \delta_t)$ or $(L - \delta_t)$, where δ_t is the change in length. The value of δ_t is given by the following equation:

$$\boxed{\delta_t = \alpha L(\Delta t)} \qquad \textbf{Eq. (9.1)}$$

The quantity α is a property of the material and is called the *coefficient of thermal expansion*. The greater the value of α, the greater the thermal movement. Plastics have the highest values of α, followed by metals and ceramic materials such as concrete, masonry,

NOTE

Units of α

The units of L and δ_t are inches, and the unit of ΔT is °F. Substituting these units in Equation (9.1), we get:

$$\text{in.} = \alpha(\text{in.})(°\text{F})$$

Because the units on both sides of the equal sign must be consistent, the units of α must be:

$$\frac{1}{°\text{F}}, \quad \text{that is,} \quad °\text{F}^{-1}$$

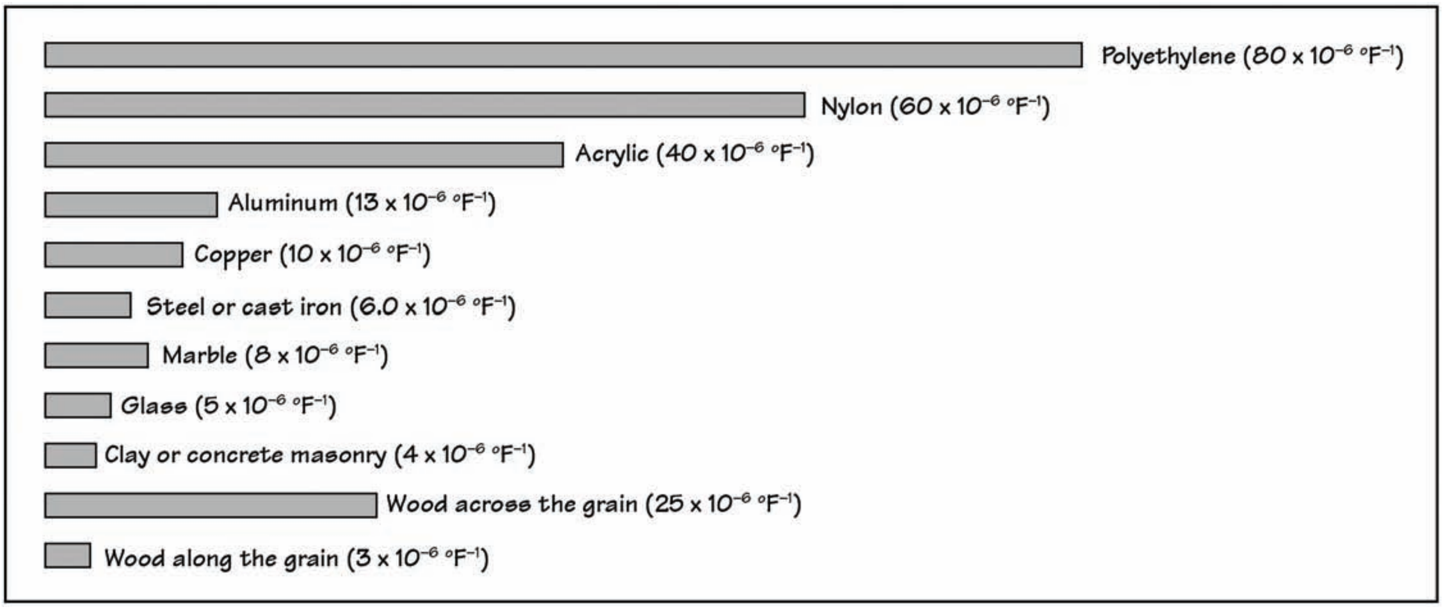


FIGURE 9.12 Approximate values of the coefficient of thermal expansion, α, of selected materials. To obtain values in $°C^{-1}$, multiply given values by 1.8. Thus, the value of α for clay or concrete masonry $= 7.2 \times 10^{-6}\ °C^{-1}$.

and glass. The units of α are $°F^{-1}$ or $°C^{-1}$. Values of α for selected materials are given in Figure 9.12.

Equation (9.1) can be used to determine the minimum width of a joint required to prevent thermal stresses between adjacent components. The value of Δt that should be used in this calculation is a function of two factors:

- *The annual temperature range to which the component is subjected.* It is the difference between the maximum and minimum temperatures of the component. Average approximate values of annual maximum and annual minimum temperatures of vertical components for the United States are shown in Figure 9.13 (10° to 110°F for the northern United States, and 20° to 120°F for the southern United States).
- *The temperature of the component at the time of its construction.* Because buildings are usually not built during times of temperature extremes, the range of ambient temperatures during which construction is undertaken is much smaller than the maximum-minimum temperature range of the component. See Figure 9.13 for typical ambient temperature ranges during construction in the United States (40° to 100°F), shown by the yellow color region.

NOTE

Component Temperature and Ambient (Air) Temperature

The temperature of building envelope components is usually not the same as the ambient air temperature. The reason is that the air temperature is recorded under shade, whereas the building envelope is exposed to the sun's radiation.

Therefore, the maximum surface temperature of an envelope component is generally higher than the maximum air temperature at the location. The difference between the two temperatures depends on the degree of exposure of the component to direct sun, its material, color, amount of insulation in the component, and the wind speed.

Dark-colored components get hotter than light-colored components. Horizontal components receive solar radiation throughout the day, so they become hotter than vertical components. Metals become hotter than nonmetals. If a component is insulated, its surface temperature is higher than that of an uninsulated component because an uninsulated component loses more heat to the interior.

Under a clear night sky, the minimum surface temperature of a component is lower than the minimum air temperature. This is due to radiation heat loss from the component to the sky, referred to as *nocturnal (nighttime) cooling*.

MAXIMUM TEMPERATURE CHANGE EXPERIENCED BY A COMPONENT

Figure 9.13 shows that the annual maximum temperature change (Δt) to which a vertical component will be subjected in the United States may be assumed to be 90°F. For roofs and other horizontal components, the value of Δt is generally higher.

9.5 MOISTURE MOVEMENT

Metals such as steel, copper, and aluminum are dimensionally stable with respect to moisture. However, Portland cement–based materials shrink due to moisture loss. Because the moisture loss continues for several weeks after construction, Portland cement–based components keep shrinking long after they are placed in a wall or slab. Therefore, concrete slabs, concrete and concrete masonry walls, and stucco require shrinkage joints—more commonly referred to as *control joints*.

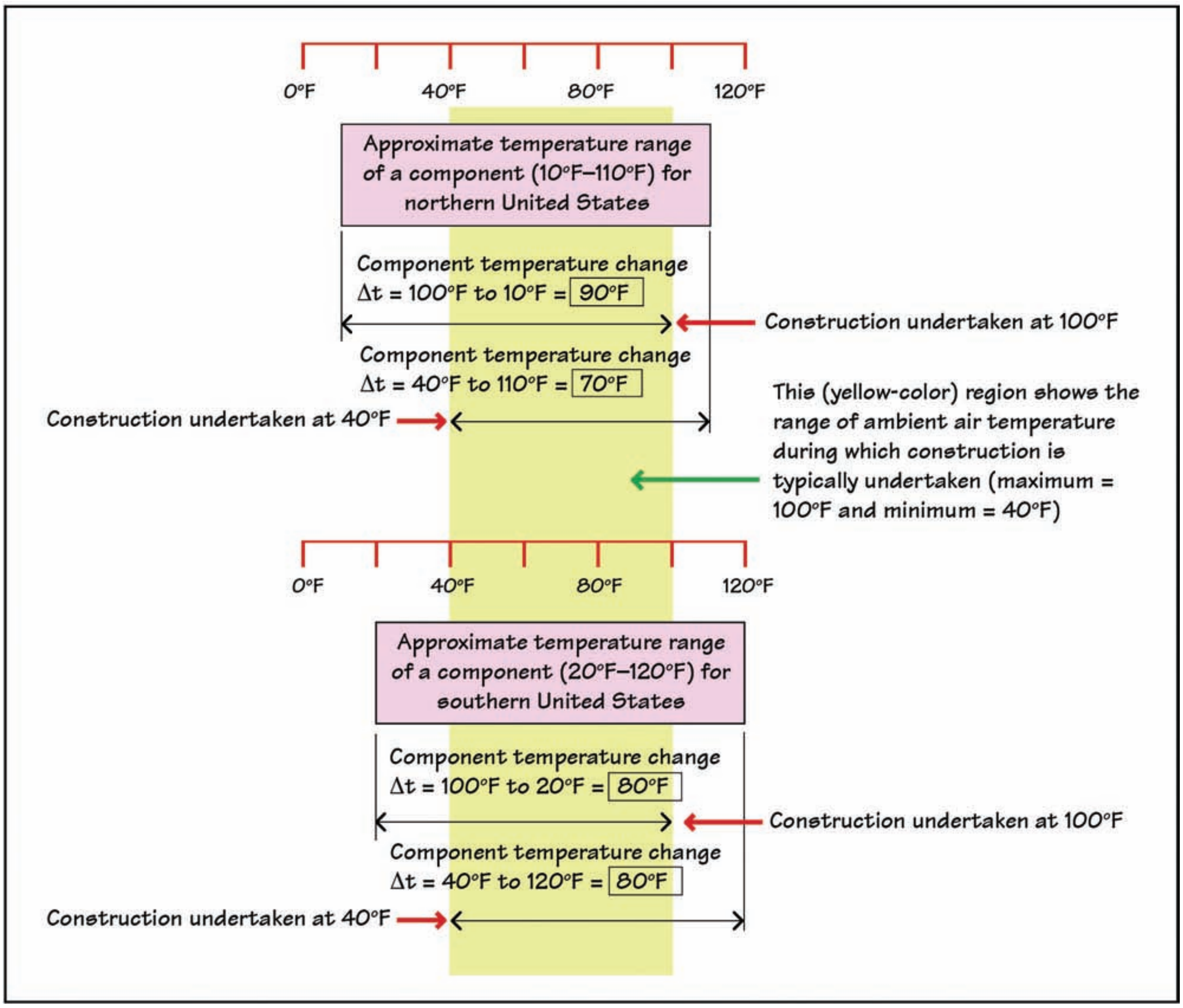

0°F
40°F
80°F
120°F
Approximate temperature range of a component (10°F–110°F) for northern United States
Component temperature change Δt = 100°F to 10°F = 90°F
Construction undertaken at 100°F
Component temperature change Δt = 40°F to 110°F = 70°F
Construction undertaken at 40°F
This (yellow-color) region shows the range of ambient air temperature during which construction is typically undertaken (maximum = 100°F and minimum = 40°F)
0°F
40°F
80°F
120°F
Approximate temperature range of a component (20°F–120°F) for southern United States
Component temperature change Δt = 100°F to 20°F = 80°F
Construction undertaken at 100°F
Component temperature change Δt = 40°F to 120°F = 80°F
Construction undertaken at 40°F

FIGURE 9.13 Annual temperature change (Δt) to which a building component is subjected in the United States. This change is the difference between the ambient air temperature when the component was constructed and the annual (maximum or minimum) temperature of the component. For example, if the component was constructed at an ambient air temperature of 100°F, the change of temperature (Δt) that the component will undergo in the northern United States is: from 100°F to 110°F = 10°F, or from 100°F to 10°F = 90°F. In the illustration, (Δt) is shown as 90°F (as a "boxed" item) for this condition because it is greater than 10°F. Similar values of (Δt) for other conditions (also shown as "boxed" items) are 70°F, 80°F, and 80°F. Thus, the maximum temperature change (Δt) that a component will be subjected to in the United States may be assumed to be 90°F. Note that this value of Δt is applicable to vertical (wall) components. Roof surfaces will see a slightly larger value of (Δt).

Estimating Thermal Movement

Example 9.1

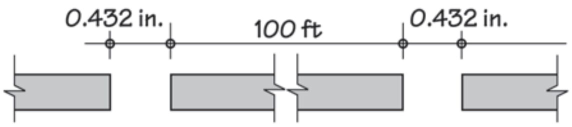
A residential neighborhood is to be provided with a clay (brick) masonry noise barrier wall along a busy road. It has been decided to use 100-ft-long segments of the wall with intervening joints. Determine the required width of each joint, considering only the wall's thermal movement.

Solution

$L = 100 \text{ ft} = 1{,}200 \text{ in.}$

$\Delta t = 90°\text{F}$ (Figure 9.13)

$\alpha = 4.0 \times 10^{-6} {}°\text{F}^{-1}$ (Figure 9.12)


0.432 in.
100 ft
0.432 in.

Minimum joint width needed to accommodate thermal movement in the 100-ft-long wall segments of Example 9.1. From Equation (9.1), the minimum joint width (δ_t) is $(4.0 \times 10^{-6})(1{,}200)90 = 0.432$ in.

Note that this joint width does not include the provision for moisture expansion, construction, and material tolerances, which should also be included in determining the total joint width (Section 9.7).

Example 9.2

A brick veneer wall is provided with continuous vertical expansion joints at 25 ft on center. Determine the required minimum width of each joint, considering the thermal expansion of the wall.

Solution

$L = 25 \text{ ft} = 300 \text{ in.}$

$\Delta t = 90°\text{F}$ (Figure 9.13)

From Equation (9.1), the joint width is $(4.0 \times 10^{-6})(3{,}000)90 = 0.108$ in.

TABLE 9.2 APPROXIMATE MOISTURE COEFFICIENT (μ) OF SELECTED MATERIALS

Material	Moisture coefficient (μ)
	Shrinkage
Plain concrete	0.0006
Reinforced concrete	0.0003
Concrete masonry	0.0003
	Expansion
Clay masonry	0.0003

MOISTURE MOVEMENT IN CONCRETE AND MASONRY

Clay (brick) masonry units expand on absorption of water or water vapor. This expansion, which occurs during and after construction, is irreversible; that is, clay masonry does not shrink on drying. In fact, a brick unit is smallest in size when it comes out of the kiln, after which it grows in size. Thus, brick masonry walls require *expansion joints*.

The amount of moisture movement in concrete and masonry is given by:

$$\boxed{\delta_m = (\mu)L} \qquad \textbf{Eq. (9.2)}$$

where δ_m is the moisture expansion or contraction of a unit of length L and μ is the *moisture coefficient* of the material. The values of μ are given in Table 9.2. Note that μ has no units. It is simply a number.

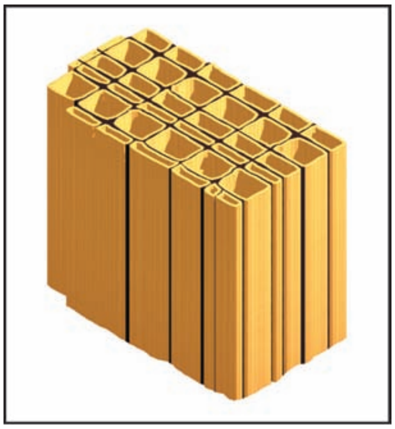


FIGURE 9.14 A simplified version of the microstructure of wood; see also Chapter 13.

MOISTURE MOVEMENT IN WOOD

As discussed in greater detail in Chapter 13, the microstructure of wood consists of hollow cellular tubes bundled together, Figure 9.14. The walls of the tubes shrink and swell, depending on the ambient air's humidity and temperature, changing the dimensions of a wood member.

The wood industry has established empirical rules for providing movement joints in wood members. For instance, a 4-ft × 8-ft plywood sheet must be provided with $\frac{1}{8}$-in. (3-mm)-wide joints at ends and edges in order to accommodate its movement. Moisture-related movement control in wood structures is discussed further in Section 15.11.

Estimating Moisture Movement

Example 9.3

Expansion joints are to be provided in a brick veneer wall at 25 ft on center. Determine the moisture expansion of each 25-ft wall segment.

Solution

From Table 9.2, the moisture coefficient, μ, of clay masonry is 0.0003. Therefore, from Equation (9.2), the moisture expansion of each 30-ft segment is

$$0.0003(25 \times 12) = 0.090 \text{ in.}$$

Example 9.4

If control joints are provided in a reinforced concrete slab-on-grade at 12-ft intervals, determine the required minimum width of each joint.

Solution

From Table 9.2, $\mu = 0.0003$. From Equation (9.2), the minimum width of each joint is

$$0.0003(12 \times 12) = 0.043 \text{ in.}$$

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. A building separation joint in a multistory building generally
   - a. runs through alternate floors, the roof, and the foundation.
   - b. runs through all floors, the roof, and the foundation.
   - c. runs through all floors and the roof.
   - d. runs through all floors and the foundation.
   - e. runs through all floors.

2. Building separation joints in a long rectilinear building are generally located at every
   - a. 500 ft on center.
   - b. 400 ft on center.
   - c. 350 ft on center.
   - d. 250 ft on center.
   - e. none of the above.

3. The width of a building separation joint is generally
   - a. $\frac{1}{2}$ in. to 1 in.
   - b. $1\frac{1}{2}$ in. to 2 in.
   - c. $2\frac{1}{2}$ in. to 3 in.
   - d. $3\frac{1}{2}$ in. to 4 in.
   - e. $4\frac{1}{2}$ in. to 5 in.

4. A seismic joint is generally similar to a building expansion joint but smaller in width.
a. True **b.** False

5. Which of the following materials has the highest coefficient of thermal expansion?
a. Steel
b. Plastics
c. Aluminum
d. Concrete
e. Glass

6. The unit of measure for the coefficient of thermal expansion (α) is
a. °C or °F.
b. feet or meters.
c. watts or joules.
d. $°C^{-1}$ or $°F^{-1}$.
e. none of the above.

7. The unit of measure for the coefficient of moisture expansion (μ) is
a. °C or °F.
b. feet or meters.
c. watts.
d. $°C^{-1}$ or $°F^{-1}$.
e. none of the above.

8. The equation used for determining the thermal movement, δ_t, of a member is
a. $\delta_t = \alpha L(\Delta t)$.
b. $\delta_t = L(\Delta t)$.
c. $\delta_t = (\alpha L)/(\Delta t)$.
d. $\delta_t = [L(\Delta t)]/\alpha$.
e. $\delta_t = [\alpha(\Delta t)]/L$.

9. Which of the following materials is subjected to moisture movement?
a. Wood
b. Concrete
c. Brick
d. All of the above
e. Only (a)

10. Which of the following materials has irreversible moisture expansion during service, that is, after construction?
a. Steel
b. Concrete
c. Brick
d. Natural stone
e. Aluminum

9.6 ELASTIC DEFORMATION AND CREEP

Consider the beam in Figure 9.15, which is initially unloaded, as shown by the dashed lines. If the beam is now loaded, it will deflect almost instantaneously in response to the load. Let the instantaneous deflected shape of the beam be represented by profile A. If this load is a permanent load, the beam's deflection may progressively increase and eventually assume the deflected profile B. This time-dependent additional deflection of the beam is known as *creep deflection*, and the associated phenomenon is called *creep*.

Thus, creep is the incremental deformation of a component caused by sustained loading. Among the structural materials used in buildings, creep is significant only in concrete and concrete masonry. Steel does not creep. In wood, creep deformation is relatively small.

Creep deformation in concrete increases progressively for up to nearly two years after the component is loaded. This implies that creep is caused only by long-term, sustained, or permanent loads. Thus, the fundamental difference between instantaneous deformation and creep deformation is that instantaneous deformation is caused by all types of loads, whereas creep deformation is caused only by the dead load.

Because building components are designed to remain elastic under loads, the instantaneous deflection is elastic. In other words, after the load is removed, the component returns to its original undeformed state. That is why instantaneous deformation is also referred to as *elastic deformation*. Creep deformation, on the other hand, is inelastic deformation of components and is, therefore, irreversible. In other words, even if the load is removed, creep deformation will remain.

Elastic deformations are routinely determined for all types of structures as part of structural calculations. For concrete structures, creep deformation is also determined. From the architectural viewpoint, the most critical deformation occurs in spandrel beams. Because spandrel beams have exterior walls anchored to them, it is necessary to provide flexibility in the anchorage of exterior walls so that neither the elastic nor the creep deflection of spandrel beams will cause additional stresses in exterior walls.

NOTE

Creep

Creep is significant in concrete and concrete masonry structures. Thus, concrete columns, particularly in high-rise buildings, keep shortening in height for up to nearly two years after their construction. A typical concrete column shortens by nearly $\frac{1}{8}$ in. (3 mm) per story due to creep. Fortunately, most creep deformation occurs in the first three months. Therefore, the shortening of columns and the consequent lowering of the floor structure have little effect on non-load-bearing walls placed under the floors. This is because it generally takes longer than three months before non-load-bearing walls are erected.

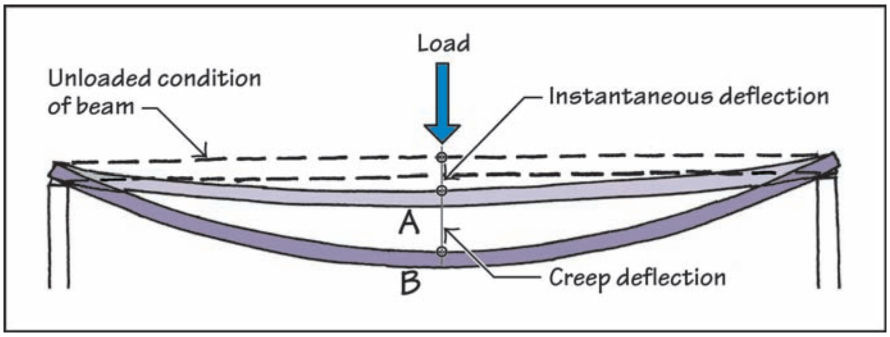


FIGURE 9.15 Instantaneous (elastic) deflection and creep (inelastic) deflection of a beam. The dashed lines show the unloaded condition of the beam.

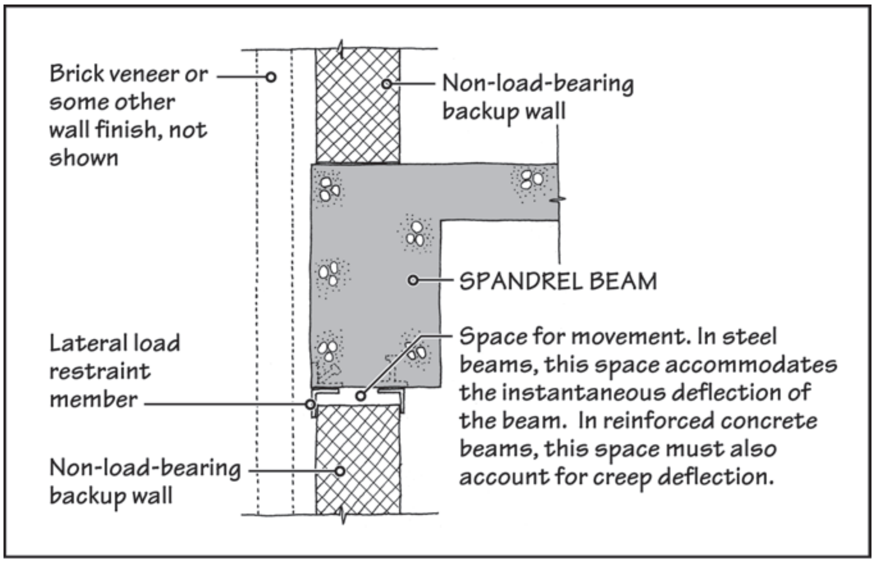

Brick veneer or some other wall finish, not shown
Non-load-bearing backup wall
SPANDREL BEAM
Lateral load restraint member
Space for movement. In steel beams, this space accommodates the instantaneous deflection of the beam. In reinforced concrete beams, this space must also account for creep deflection.
Non-load-bearing backup wall

FIGURE 9.16 The connection between the spandrel beam and the non-load-bearing wall below must account for the beam's deflection (see also Figure 28.6).

NOTE

Spandrel Beam

A spandrel beam is a beam that runs on the outside edge of a floor or roof of the building; see Figure 9.16.

If a non-load-bearing wall is placed directly under a spandrel beam, an adequate space between the beam and the top of the wall should be provided to allow the beam to deflect under the load, Figure 9.16. If adequate space is not provided, the load from the beam will be transferred to the wall, damaging it.

9.7 TOTAL JOINT DIMENSION

In addition to thermal, moisture, elastic, and creep deformations, there are several other factors that should be considered in determining the joint dimensions. One such important consideration is material tolerances to recognize that building components vary from their specified dimensions. For example, it is not uncommon to see brick or concrete masonry units that are undersized or oversized. Noticeable differences in dimensions from those stated on the drawings can occur in prefabricated concrete curtain wall panels.

In addition to material or component tolerances, construction tolerances should be taken into account. For instance, an expansion joint in a masonry wall may be shown as a vertical joint on the drawings, but the constructed joint is unlikely to be absolutely vertical. Construction tolerances are a function of quality control during construction. Smaller tolerances require good construction practices and supervision. Poor supervision demands larger tolerances. Therefore:

$$\boxed{\begin{array}{l}\text{Width of}\\ \text{joint}\end{array} = \begin{array}{l}\text{width based on}\\ \text{temperature, moisture,}\\ \text{and other movements}\end{array} + \text{tolerances}} \qquad \textbf{Eq. (9.3)}$$

Additionally, foundation settlement and story drift (see Principles in Practice in Chapter 19) due to wind or earthquake loads are important. Some chemical processes may also cause movement. Steel expands as it corrodes. Excessive corrosion of steel can cause cracking and sometime spalling of concrete. Because water expands on freezing, the freezing of water causes similar effects in materials that absorb water, such as brick, concrete, concrete masonry, and wood.

EFFECT OF A SEALANT ON JOINT DIMENSION

Most joints in building envelope components are filled with elastomeric sealants. The sealants have a finite ability to cyclically stretch and compress, which is given as the plus-minus movement ability of the sealant. The plus value denotes the maximum stretch the sealant can withstand, and the minus value denotes the maximum compression it can sustain.

In fact, sealants are generally classified based on their movement ability. Thus, a sealant with a movement ability of ±25% is called a *class 25 sealant*. Such a sealant is able to stretch and compress by 25% of its installed dimension. Similarly, a sealant with a movement ability of ±50% is called a *class 50 sealant*. Thus, if the width of a joint at the time the sealant is applied to it is 1 in., a class 50 sealant will safely stretch to 1.5 in. or compress to 0.5 in.

The movement ability of sealants must be included in determining the total joint width of a sealed joint. Therefore, the total joint width of a sealed joint is given by

$$\boxed{\begin{matrix}\text{Joint width of}\\ \text{sealed joint}\end{matrix} = \frac{100}{\text{sealant class}}\,[\text{joint movement}] + \text{tolerances}} \qquad \textbf{Eq. (9.4)}$$

Estimating Total Joint Width Between Components

Example 9.5

Continuous vertical expansion joints are to be provided in a brick veneer wall at 25 ft on center. Determine the total joint width, assuming that the joints are sealed with a class 50 sealant.

Solution

From Examples 9.2 and 9.3, the thermal and moisture movement of a 25-ft-long wall is $0.108 + 0.090 = 0.198 =$ in. From Equation (9.4), total joint width is

$$\frac{100}{50}(0.198) = 0.396 \text{ in.}$$

This joint width does not include tolerances. In practice, the expansion joints in a brick veneer wall should be $\frac{1}{2}$ in. (0.5 in.) wide.

9.8 PRINCIPLES OF JOINT DETAILING

In detailing a movement joint in a component, it is important to distinguish between an *expansion joint* and a *control* (*shrinkage*) *joint*. Because the joint width in an expansion joint will become smaller over time, the filler in an expansion joint (if used) must be elastomeric to allow unrestrained movement of the components.

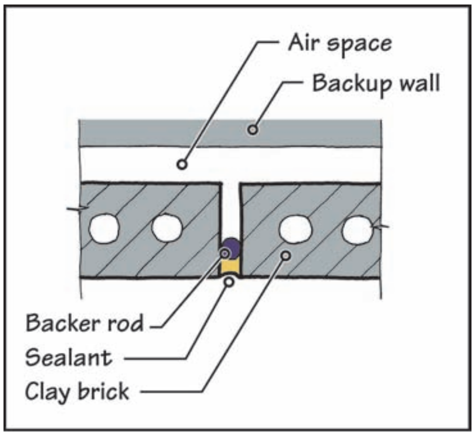


FIGURE 9.17 Detail of an expansion joint in a brick veneer wall. The joint is filled with a compressible backer rod and an elastomeric sealant (see also Figure 28.16).

The filler in a control joint, on the other hand, may be elastomeric or nonelastomeric. If a nonelastomeric filler is provided in a control joint, the detailing of the joint must allow unrestrained shrinkage of the components.

The difference in the detailing of an expansion joint and a control joint can be further appreciated by examining typical joint details used in brick masonry and concrete masonry walls. As stated earlier, brick masonry walls expand over time after construction as the bricks absorb water from the mortar and the atmosphere. Therefore, brick masonry walls require expansion joints. By contrast, concrete masonry walls shrink after construction as the water used in manufacturing concrete masonry units and in the preparation of mortar evaporates. Therefore, concrete masonry walls require control joints.

Figure 9.17 shows the detailing of an expansion joint in a brick veneer wall. Note that the joint is filled with a compressible backer rod and an elastomeric sealant.

Figure 9.18 shows a typical control joint detail in concrete masonry walls. The joint is filled with masonry mortar to provide shear key between the two parts of the wall. To ensure that the mortar does not adhere on both sides of the joint and restrain the shrinkage of the wall, asphalt-saturated paper is placed on one side of the joint to break the bond.

In explaining the difference between a control joint and an expansion joint, we considered moisture-induced movement in brick and concrete masonry walls, which is

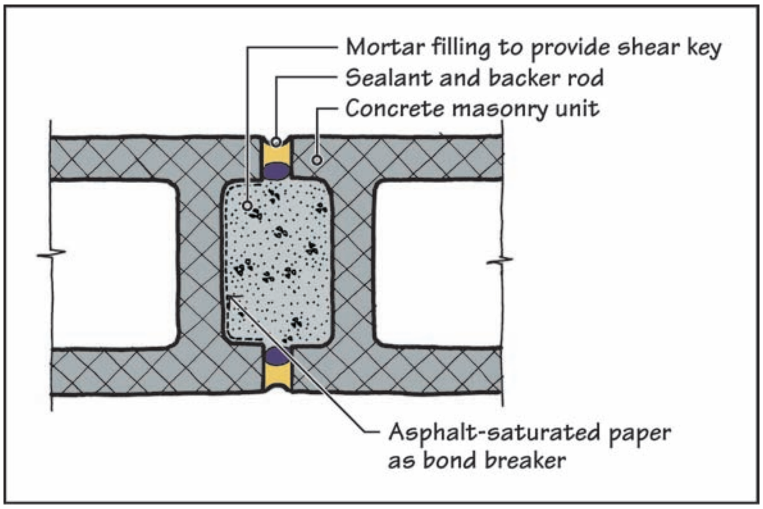

Mortar filling to provide shear key
Sealant and backer rod
Concrete masonry unit
Asphalt-saturated paper as bond breaker

FIGURE 9.18 Detail of a control joint in a concrete masonry wall (see also Figure 25.25).

largely permanent. On the other hand, to accommodate reversible movement, such as that created by temperature changes, requires either an open joint or one filled with an elastomeric sealant (Figure 9.17). In other words, an open joint or an elastomerically filled joint is a versatile joint.

Note that because temperature-induced movement is almost universal, expansion joints are provided in most components. Control joints, on the other hand, are provided in concrete and concrete masonry components. Detailed discussion of joint detailing are provided in later chapters. For example, construction joints, control joints, expansion joints, and isolation joints used in concrete construction are covered in Chapter 22.

9.9 COMPONENTS OF A SEALED JOINT

The primary purpose of sealing a joint is to prevent water penetration. However, control of air leakage, dust penetration, and noise transmission are additional benefits of sealing a joint. An unsealed joint may also get filled with incompressible materials over time, resulting in joint failure.

Although joint sealant is the most important component of a sealed joint, these other components must also be carefully selected:

- Substrate
- Primer
- Sealant backup
- Bond breaker

SUBSTRATE

For a sealed joint to function effectively, it is important that the sealant be fully adhered to the surfaces of components meeting at the joint (called the *substrate*). A nonadhering sealant will obviously result in a leaky joint.

The adhesion of the sealant to the substrate depends on the chemical compatibility of the sealant with the substrate material. Because all sealants are not compatible (or equally compatible) with all substrate materials, it is important to obtain compatibility information from the sealant manufacturer. This is particularly vital because substrate materials such as concrete and masonry are sometimes treated with water-repellent chemicals, and metals are sometimes treated with paints and other protective coatings. These treatments may inhibit sealant adhesion.

Some substrate materials may require special joint preparation, such as the application of primers to make the substrate compatible with the sealant. In any event, some preparation will be required on all substrates, including cleaning the surfaces of loose particles, contaminants, frost, ice, and so on.

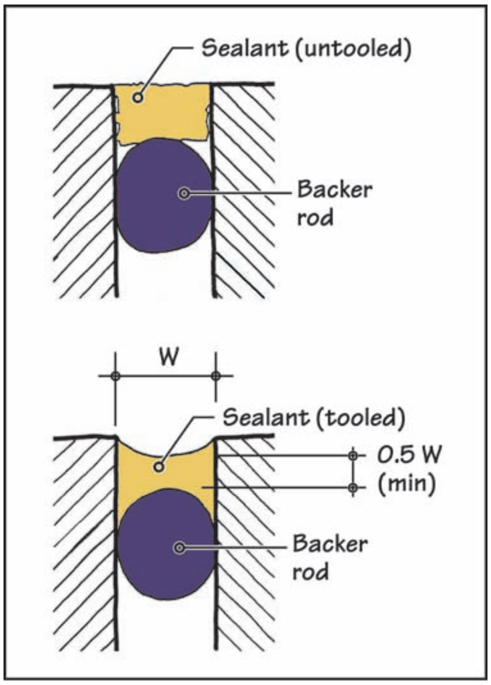


FIGURE 9.19 Untooled and tooled sealants in joints. Note that the depth of the sealant must be at least half the width of the joint.

PRIMER

The purpose of a primer is to improve the adhesion of a sealant to the substrate. Some sealants require primers on all types of surfaces, whereas others require primers on a few types of surfaces. Most sealant manufacturers require primers for concrete and masonry substrates to stabilize the substrate by filling the pores and strengthening weak areas.

Some sealants require different primers for different substrates, which is an important consideration in the selection of a sealant if disparate materials are to be joined. Another consideration is the length of time that must pass between the application of the primer and the sealant. Obviously, a sealant that can be applied almost immediately after the application of the primer is preferable.

SEALANT BACKUP—THE BACKER ROD

A sealant backup is a compressible and resilient material, such as a plastic foam. It is usually circular in cross section; hence, it is called a *backup rod* or, more commonly, a *backer rod*. The diameter of the backer rod should be greater than the width of the joint so that it is held in place by compression. The backer rod performs the following functions:

- It controls the depth and shape of the sealant.
- It allows tooling of the sealant, which provides adhesion between the sealant and substrate. In an untooled joint, the sealant will not fully adhere to the substrate, resulting in a leaky joint. A properly tooled joint, on the other hand, will have full contact with the substrate, Figure 9.19. For the joint to be tooled, the backer rod must be under sufficient compression not to slide under the pressure of tooling.
- It acts as a temporary joint seal until the sealant is applied.

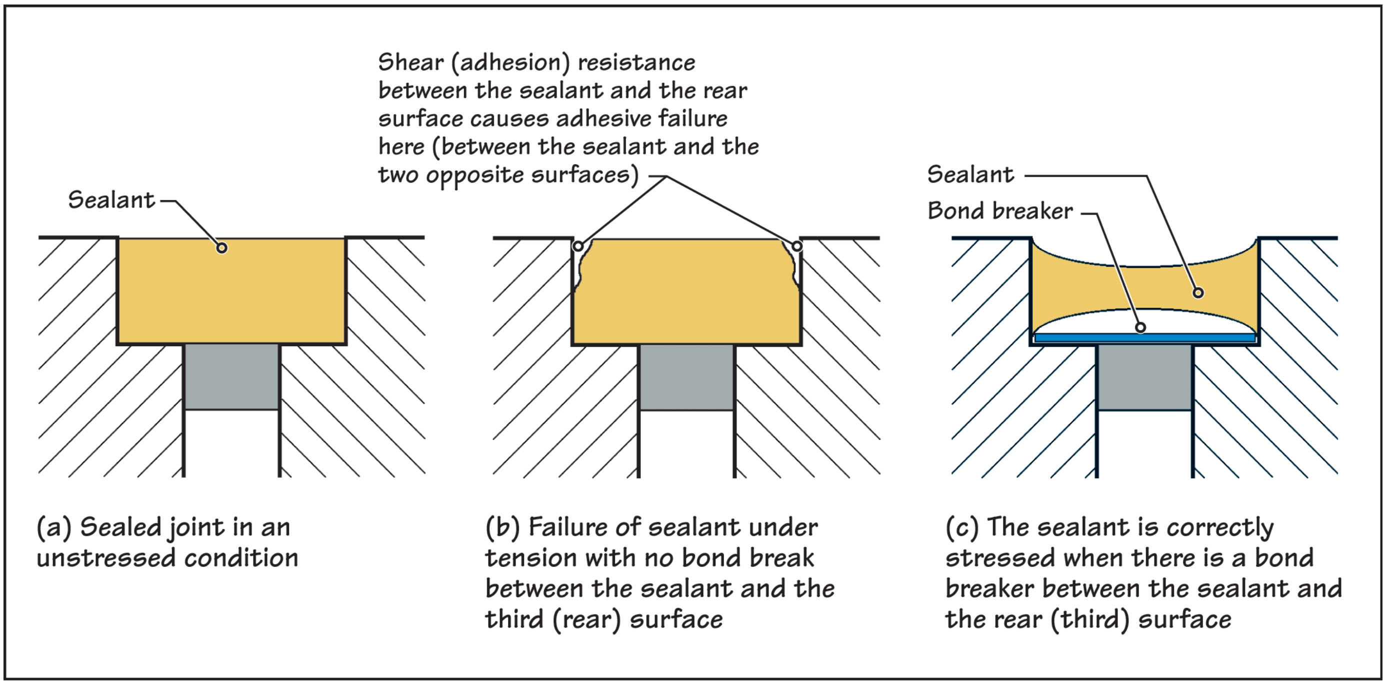

Shear (adhesion) resistance between the sealant and the rear surface causes adhesive failure here (between the sealant and the two opposite surfaces)
Sealant
Sealant
Bond breaker
(a) Sealed joint in an unstressed condition
(b) Failure of sealant under tension with no bond break between the sealant and the third (rear) surface
(c) The sealant is correctly stressed when there is a bond breaker between the sealant and the rear (third) surface

FIGURE 9.20 An ideal sealed joint should only be bonded to two opposite surfaces so that the sealant is subjected to either tension or compression. A bond between the sealant and the third (in this case, the rear) surface may cause sealant failure, as shown in **(b)**, because of the adhesion of sealant to the third surface. Therefore, where a third surface exists in a sealed joint, a bond breaker should be used, as shown in **(c)**.

For the backer rod to function as a secondary seal, it must remain elastic throughout its life and not develop significant compression set. It should also be compatible with the sealant. Therefore, a backer rod approved by the sealant manufacturer should be used.

Bond Breaker

For the sealant to function effectively, it should be bonded to only two opposite surfaces of the substrate so that it comes under axial tension or axial compression when the joint moves. If a joint is similar to the one shown in Figure 9.20(a), a bond breaker is necessary on the rear side of the joint to prevent sealant failure, shown in Figure 9.20(b).

A bond breaker is required only if the third surface is hard and unyielding, such as concrete, metal, masonry, or any other inflexible backup. A bond breaker is not required with a flexible backup that will not significantly restrict the freedom of sealant movement. Thus, a bond breaker is not required in a conventional joint with a foam backer rod, such as that shown in Figure 9.19.

9.10 TYPES AND PROPERTIES OF JOINT SEALANTS

Joint sealants may be divided into three categories:

- Preformed tapes
- Caulks
- Elastomeric sealants

Preformed tapes are available in rolls. They function as seals only if they are under pressure; they are commonly used in window glazing, door jambs, and gypsum drywall.

Caulks are doughlike materials and are the first generation of sealing compounds. Glazing putty is an example of the earliest caulks used in buildings. It consists of nearly 12% linseed oil and 88% chalk (calcium carbonate) that hardens as it cures (oil evaporation), leading to cracking, loss of elasticity, and, hence, loss of its sealing ability. It is rarely used today.

Types of Elastomeric Sealants

Elastomeric sealants are synthetic materials (polymers) and are the ones most commonly used in contemporary construction. The five commonly used synthetic sealants are:

- Polyisobutylene
- Acrylics
- Polyurethane
- Polysulfide
- Silicone

Polyisobutylene and acrylic sealants have very low movement ability and are used as caulking materials in joints that do not move or move very little, such as the static joints between aluminum window frames. Polyisobutylene (referred to as *butyl caulk*) has excellent resistance to water-vapor transmission. Therefore, it is commonly used as the primary seal in an insulating glass unit. The secondary seal in an insulated glass unit is provided by the silicone sealant because of its durability and good adhesion (Section 30.6).

Polyurethane sealant has high abrasion resistance. Therefore, it is the sealant of choice in horizontal joints subjected to foot traffic. It has good compatibility with a wide variety of substrates—another factor in its favor.

Polysulfide sealant has excellent chemical and weathering resistance. It is the sealant of choice for swimming pools, wastewater treatment plants, water-treatment plants, and so on, where a durable watertight seal is required. Silicone sealant has high strength and exceptional resistance to ultraviolet radiation. It is the only sealant that can be used in structural glazing.

Table 9.3 gives a comparative overview of three of the most commonly used sealants—polyurethane, polysulfide, and silicone—and the following sections provide a description of the criteria that must be considered in their selection.

MOVEMENT ABILITY OF SEALANTS

The most important property of a sealant is its ability to withstand cyclic joint movements (Section 9.7). Currently available sealants are classified into three categories: low-range sealants, medium-range sealants, and high-range sealants.

A low-range sealant has limited movement ability, of the order of ±5% or less. These sealants include: (a) oil-based caulks, and (b) butyl or acrylic caulks. Low-range sealants should be used only in a nonmoving joint. Their principal advantage lies in their low cost.

Medium-range sealants have a movement range of up to ±12.5%, and high-range sealants have a movement range larger than ±12.5%. Silicone sealants normally have the highest movement capability, up to ±50%.

NOTE

Modulus of a Sealant

From Equation (4.3), the stress in a material is the product of the modulus of elasticity of the material and the strain:

Stress = modulus of elasticity × strain

Thus, stress in a material is directly proportional to its modulus of elasticity. In other words, a low-modulus material will be subjected to lower stress than a high-modulus material if the strain (deformation) of the two materials is the same.

STRENGTH AND MODULUS OF SEALANTS

A sealant must be able to withstand movement stresses. Most joint failures occur due to excessive tensile stress. Tensile failure may occur either at the substrate-sealant interface (failure due to inadequate adhesion) or within the sealant (failure due to inadequate cohesion).

Modulus refers to the modulus of elasticity of sealant, a measure of the stiffness of a material (Chapter 4). A high-modulus sealant is stiffer than a low-modulus sealant and is desirable where joint movement is small. Thus, a high-modulus sealant is required in structural glazing, where the stiffness of the joint between the glass and the aluminum frame is important. A low-modulus sealant, on the other hand, is desirable where joint movement is large and the sealant is required purely for sealing purposes. A low-modulus sealant will be under lower stress due to movement.

TOOLING TIME, CURE TIME, AND TEMPERATURE RANGE

Tooling time refers to the time (usually measured in minutes) that must be allowed to elapse before the sealant changes from a liquid state to a semisolid state so that it can be tooled. *Cure time* refers to the time it takes for the sealant to be hardened to its final elastomeric state.

TABLE 9.3 COMPARATIVE OVERVIEW OF COMMONLY USED SEALANTS

		Type of sealant	
Sealant property	**Polyurethane**	**Polysulfide**	**Silicone**
Movement ability	Up to ±25%	Up to ±25%	Up to ±50%
Water-vapor permeability	Fair	Good	Poor
Abrasion resistance	Excellent	Poor	Fair
Chemical resistance	Fair	Excellent	Fair
Durability	Good	Good	Excellent
Substrate compatibility	Excellent	Good	Incompatible with some substrates
Paintability	Good	Good	Poor

Application temperature range refers to the ambient air temperature range within which the sealant can be applied. *Performance temperature range* is the range over which the sealant will maintain its properties after it has cured.

LIFE EXPECTANCY OF SEALANTS

Life expectancy is the time (in years) after which the sealant may have to be reapplied. Most high-grade sealants, such as the structural silicones, are quoted by their manufacturers to have a life expectancy of 20-plus years.

ONE-PART OR TWO-PART SEALANTS

Sealants can either be one-part or two-part sealants. One-part sealants are easier to use but generally take longer to cure and have long tack-free time. Longer curing time means a greater delay in tooling and possible damage to the sealant if the joint moves excessively before the sealant has fully cured. Long tack-free time means that the sealant will tend to attract more dirt.

NOTE

Joints in Building Components—Lapped Joints

There are several movement joints in buildings that function because of the overlap between building components. Such joints generally do not need to be sealed. Some examples of lapped joints are joints between exterior wall siding (Chapter 16), joints between roof shingles or tiles, and joints between underlayment felts below the shingles (Chapter 34).

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

11. Creep deformation occurs in
- **a.** concrete members.
- **b.** steel members.
- **c.** aluminum members.
- **d.** all of the above.

12. Creep deformation is caused by
- **a.** live loads.
- **b.** dead loads.
- **c.** wind loads.
- **d.** all of the above.
- **e.** none of the above.

13. A spandrel beam in a building is a beam that
- **a.** has a floor slab or roof slab on both sides.
- **b.** runs on the outside edge of a floor or roof.
- **c.** is partially embedded in the ground.
- **d.** is supported by a continuous wall below it.
- **e.** supports a continuous wall above it.

14. A non-load-bearing wall that runs under a spandrel beam should be adequately separated from the beam to allow the beam to move freely in the
- **a.** vertical direction.
- **b.** horizontal direction.
- **c.** both (a) and (b).

15. In determining the total width of a movement joint between building components, we account for the dimensional and construction tolerances. Poor or inadequate quality control on a construction site
- **a.** increases construction tolerances.
- **b.** decreases construction tolerances.
- **c.** increases dimensional tolerances.
- **d.** decreases dimensional tolerances.
- **e.** none of the above.

16. A joint between two walls has been determined to be 0.5 in. if the joint is not to be filled with a sealant. If the same joint is to be filled with a class 50 sealant, its width should be
- **a.** 1 in. minimum.
- **b.** $2\frac{1}{2}$ in. minimum.
- **c.** $\frac{1}{4}$ in. minimum.
- **d.** $\frac{1}{4}$ in. maximum.
- **e.** none of the above.

17. Which of the following materials does not represent a joint sealant?
- **a.** Silicone
- **b.** Polysulfide
- **c.** Polyisobutylene
- **d.** Polyvinyl chloride

18. Which of the following joint sealants has the highest abrasion resistance?
- **a.** Polyisobutylene
- **b.** Acrylic
- **c.** Polyurethane
- **d.** Silicone

19. Which of the following joint sealants has the highest movement ability?
- **a.** Polyurethane
- **b.** Acrylic
- **c.** Polyisobutylene
- **d.** Silicone

20. The sealant in a joint works best when it is subjected to
- **a.** tension, compression, and shear.
- **b.** tension, compression, shear, and bending.
- **c.** tension or shear only.
- **d.** tension or compression only.

REVIEW QUESTIONS

1. Using sketches and notes, explain the various types of movement joints used in buildings.
2. Explain the relative suitability of a static joint versus a dynamic (movement) joint in buildings.
3. With the help of a sketch, explain why and where building separation joints should be provided.
4. Explain the differences between a seismic joint and a building separation joint.
5. What is creep, and how does it affect the movement of building components? Explain.
6. Explain why a low-modulus sealant is generally preferred over a high-modulus sealant.
7. Silicone, polyurethane, and polysulfide are commonly used as joint sealants. Explain their relative suitability for various applications.
8. Discuss the benefits of tooling a joint sealant.

CHAPTER 10

Principles of Sustainable Construction

CHAPTER OUTLINE

10.1 MAJOR MILESTONES IN SUSTAINABLE BUILDING DESIGN AND CONSTRUCTION

10.2 FUNDAMENTALS OF SUSTAINABLE BUILDINGS

10.3 LEED AND THE SUSTAINABILITY RATING OF A BUILDING

10.4 ATTRIBUTES OF SUSTAINABLE BUILDING MATERIALS

10.5 MATERIAL SUSTAINABILITY ATTRIBUTES 1 TO 4—RENEWABILITY, LOCAL PRODUCTION, RECYCLABILITY, AND RECOVERY AND REUSABILITY

10.6 MATERIAL SUSTAINABILITY ATTRIBUTE 5—ENVIRONMENTAL PRODUCT DECLARATIONS (EPD)

10.7 MATERIAL SUSTAINABILITY ATTRIBUTE 6—HEALTH PRODUCT DECLARATIONS (HPD)—THE MATERIAL INGREDIENTS

10.8 CRADLE-TO-CRADLE CERTIFICATION (C2C) OF BUILDING PRODUCTS—AN ALTERNATIVE TO EPD AND HPD

10.9 PRODUCT SUSTAINABILITY BASED ON A SINGLE ATTRIBUTE OR A LIMITED SET OF ATTRIBUTES

10.10 UNIVERSAL BASELINE BUILDING SUSTAINABILITY—THE INTERNATIONAL GREEN CONSTRUCTION CODE

Before the beginning of the twentieth century, buildings contributed little to environmental degradation. Building construction was largely craft based, and most buildings were built by human labor or low-tech tools, occasionally using simple machines. The use of locally produced materials was the norm, and the amount of energy used in mining raw materials and converting them into finished products (referred to as *embodied energy*) was low.

In addition to low embodied energy, the energy used in a building's operation and maintenance (lighting, heating, cooling, water supply, and waste disposal) was low. Air conditioning had not yet been invented. The dominant source of interior illumination was daylight, and the levels of artificial lighting in buildings were modest.

INVENTION OF MECHANICAL AIR CONDITIONING

Around the beginning of the twentieth century, several technical innovations changed the way buildings were constructed and used. The most significant change was the invention of air conditioning (by Willis Carrier in 1902). This produced a ducted system of comfort conditioning using warm or chilled air. By the middle of the twentieth century, most new buildings in North America were fully air conditioned—a technology that spread not only to buildings throughout the world but also to forms of transportation that carried people and perishable goods (trains, buses, and automobiles). The result was a hefty increase in the world's energy use.

PASSENGER ELEVATORS AND GLASS-CLAD SKYSCRAPERS

Another major development was the elevator developed by Elisha Graves Otis, who publicly demonstrated its safety in 1854 in New York City. The elevator's safety, and the subsequent improvements in its efficiency and speed provided the necessary stimuli for the construction of tall buildings. Initially, Chicago and New York City—and later other urban centers throughout the world—began constructing tall buildings, giving birth to an entirely new building form, the skyscraper.

The amount of energy required for the construction of a square foot of a skyscraper is far greater than that required for the construction of a low- or mid-rise building. This is due not only to the use of heavy construction equipment (excavators, bulldozers, graders, loaders, cranes, etc.) required for the construction of a skyscraper but also to the disproportionately large amount of materials needed in its structural frame.

In addition to a large amount of embodied energy, there is a preference for cladding tall buildings in glass driven by its aesthetics, transparency, and lightweight. This means that tall buildings also consume large amounts of energy for operation and maintenance. On the other hand, because tall buildings yield denser urban habitations, they reduce the amount of energy required for urban infrastructure—roads, water supply, sewage, and waste-disposal facilities. The net effect, however, is one of relatively greater energy consumption of both—embodied and recurring—per square foot of building area.

THE 1970S AND THE ENVIRONMENTAL REVOLUTION

The escalation of energy use continued unabated until the oil embargo of 1973. Although the reason for the embargo was entirely political, it jolted the world to the realization of its excessive dependence on energy and the pace at which the earth's finite energy resources were being depleted. Additionally, around the same time, the concern was rising among the scientists about the possible thinning of the ozone layer in the earth's atmosphere and its damaging impact on the environment—also due to the world's excessive energy use. This fact was validated by detailed measurements made in 1987 [Ref. 10.1]. In other words, the early 1970s witnessed not just a growth in the realization of our abuse of planet's resources but also in the damage it was causing to our entire ecosystem—air, water, land, etc. The beginning of 1970 may, therefore, be considered as the dawn of the *environmental revolution*.

The environmental revolution led to the concept of pursuing an *ecologically benign*, or e*nvironmentally friendly*, existence. The term *sustainable development* eventually stuck because it included the dimension of time. Another commonly used term is *green development*, which emphasizes its association with the environment.

This chapter begins with a discussion of the fundamentals of sustainability as applied to building design and construction. Subsequently, it focuses on the issues of sustainability as applied to materials and construction. It is important to note that buildings are large consumers of natural resources, as depicted in Figure 10.1. Therefore, even a modest decrease in resource consumption by buildings or the use of environmentally friendly materials can have a substantial impact on the environment.

NOTE

Embodied Energy in a Building

The embodied energy in a building is the amount of energy consumed by all the processes involved in the production of a building—from the acquisition of raw materials to the delivery and placement of the final product in the building. It includes the energy used in mining, manufacturing, transportation, construction, and administrative functions.

Embodied Energy in a Product

The embodied energy in a material or product is the amount of energy used in its production, including the administrative functions related to its production. It does not include the energy used in the product's transportation to the construction site and its installation in the building.

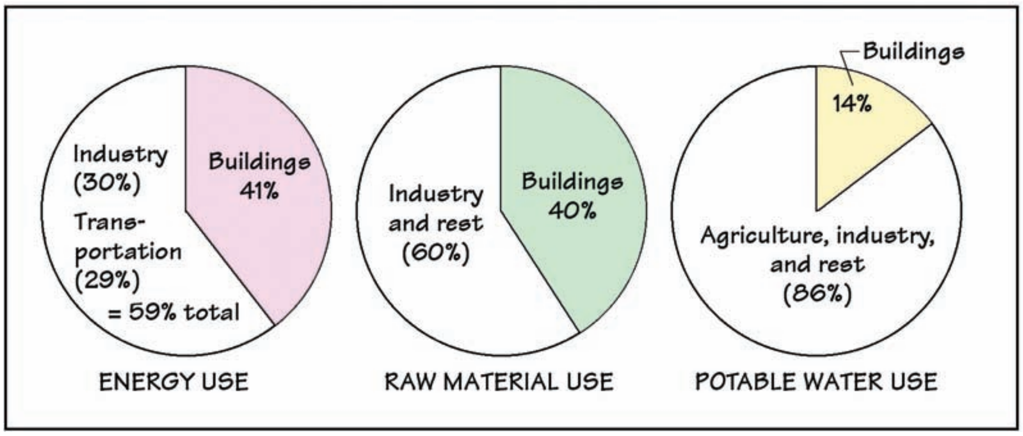


FIGURE 10.1 Natural resources (energy, raw materials, and potable water) consumed by buildings in the United States [Refs. 10.2 and 10.3].

10.1 MAJOR MILESTONES IN SUSTAINABLE BUILDING DESIGN AND CONSTRUCTION

The first serious worldwide discourse on sustainable development is generally traced to the (1987) United Nations publication known as the *Brundtland Report* and entitled: *Our Common Future*. The report was named after Gro Brundtland, prime minister of Norway, who chaired the UN World Commission on Environment and Development [Ref. 10.4]. The gist of the report is best described by the following excerpt:

> *. . . the challenge faced by all is to achieve sustainable world economy where the needs of all the world's people are met without compromising the ability of the future generations to meet their needs.*

Since the publication of the Brundtland Report, sustainability has become an all-encompassing discipline because truly sustainable development must include all facets of human activity—agriculture, manufacturing, transportation, buildings, and infrastructure.

With respect to sustainable buildings, the first major step is generally credited to the U.K.'s Building Research Establishment (BRE), which launched a sustainability rating system for buildings in 1990, known as BREEAM (an acronym for Building Research Establishment's Environmental Assessment Method). This was followed by the establishment in 1993 of the United States Green Building Council (USGBC), which launched its first sustainability rating system, known as *Leadership in Energy and Environmental Design (LEED)* in 1998. The various important milestones reached with respect to sustainable building design and construction, and the assessment of building sustainability in the United States are illustrated in Figure 10.2.

FOCUS ON THE INTERRELATIONSHIP BETWEEN BUILDINGS AND THE ENVIRONMENT

It is often argued that, excepting the brief period between World War II and the work initiated by BRE and USGBC in the 1990s, architects generally designed buildings in harmony with the (natural) environment by considering building orientation, natural ventilation, exterior shading devices, passive solar, landscape features, use of local materials, and so on. While this is true, the environmental revolution pushed us to consider not just the impact of environment on building design but also the converse of it, that is, the impact of buildings (the built environment) on the (natural) environment, Figure 10.3.

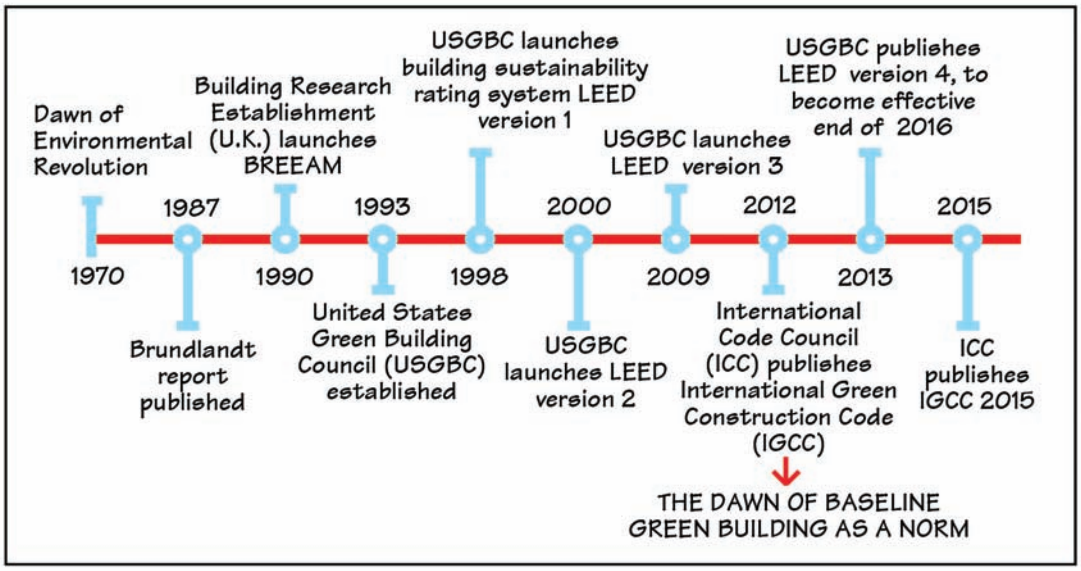

Dawn of Environmental Revolution
1970
1987
Brundlandt report published
Building Research Establishment (U.K.) launches BREEAM
1990
1993
United States Green Building Council (USGBC) established
USGBC launches building sustainability rating system LEED version 1
1998
2000
USGBC launches LEED version 2
USGBC launches LEED version 3
2009
2012
International Code Council (ICC) publishes International Green Construction Code (IGCC)
THE DAWN OF BASELINE GREEN BUILDING AS A NORM
USGBC publishes LEED version 4, to become effective end of 2016
2013
2015
ICC publishes IGCC 2015

FIGURE 10.2 Major milestones in the advancement of green building design and construction.

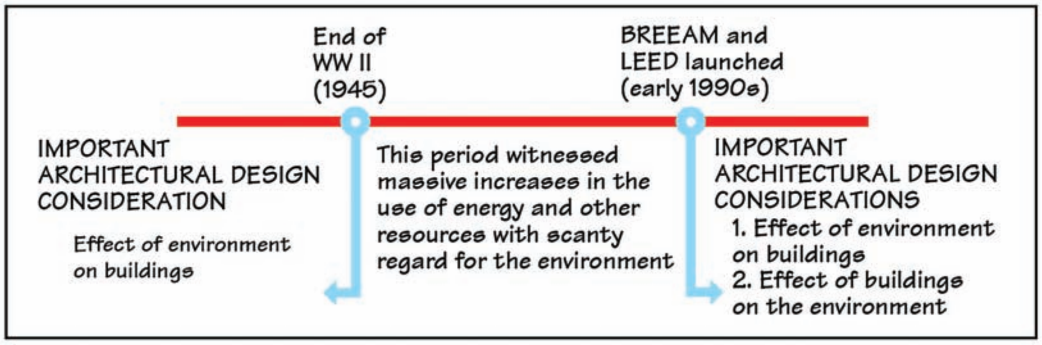

End of WW II (1945)
BREEAM and LEED launched (early 1990s)
IMPORTANT ARCHITECTURAL DESIGN CONSIDERATION
Effect of environment on buildings
This period witnessed massive increases in the use of energy and other resources with scanty regard for the environment
IMPORTANT ARCHITECTURAL DESIGN CONSIDERATIONS
1. Effect of environment on buildings
2. Effect of buildings on the environment

FIGURE 10.3 Environment as an architectural design consideration before the mid-twentieth century and after the environmental revolution.

10.2 FUNDAMENTALS OF SUSTAINABLE BUILDINGS

The fundamentals of a sustainable building are commonsense, and may be grouped under two categories: (a) design and (b) construction.

Design

- Site design and design of buildings for low natural resource consumption in materials and assemblies comprising the building, and in the building's operation and maintenance (O+M).
- Specify materials with low impact on: (a) the environment and (b) human health.
- Design the building and the neighborhood to maximize development density, minimize transit distances, and promote quality of human life and protect the biosphere.

Construction

- Reduce construction waste and establish environment-friendly waste management plan.
- Reduce environmental pollution caused by soil erosion, waterway sedimentation, and airborne dust generation during construction.

While the above classification gives a summary outline of a sustainable building, a more detailed classification is used in LEED sustainability rating system outlined in the following section.

10.3 LEED AND THE SUSTAINABILITY RATING OF A BUILDING

Without standards to guide the design and construction for sustainability, it is difficult for a designer to make decisions that successfully address the numerous diverse and interrelated sustainability issues encountered in a project. For that reason, several organizations have worked for years to develop objective, practical, and judicious systems to rate the sustainability of buildings of various types.

As stated in Section 10.1, the organization that has become a key player in the United States and globally is the U.S. Green Building Council (USGBC). Like all sustainability ratings, USGBC's rating system is voluntary, consensus based, and provides a third-party, independent measure of a building's sustainability. It is called the *Leadership in Energy and Environmental Design (LEED®) Green Building* rating system.

ENVIRONMENTAL IMPACT CATEGORIES

In LEED rating system, the sustainability of a building is assessed under the following six environmental categories, known as the *impact categories*, listed hereunder and illustrated in Figure 10.4.

1. Location and Transportation (LT)
2. Sustainable Sites (SS)
3. Water Efficiency (WE)
4. Energy and Atmosphere (EA)
5. Materials and Resources (MR)
6. Indoor Environmental Quality (EQ)

Impact categories 1 and 2 deal with the site, and 3 to 6 cover the building. In each of the six categories several requirements that contribute to the overall sustainability of the building are enumerated in a rating system. Each requirement has a numerical weighting associated with it that gives its relative importance in achieving overall sustainability. Some requirements that have no weighting assigned, are prerequisites, and are mandatory. A few of the important requirements in each impact category are shown in Figure 10.4.

The reader is urged to carefully go through the requirements shown in Figure 10.4 to obtain a broad understanding of the sustainability issues addressed in each category. An important point to notice in impact categories on energy and water is the requirement of separate metering for various uses in a building. This requirement lays emphasis on an ongoing post-occupancy evaluation of the use of these two important resources, and helps the commissioning process. The commissioning process (explained later in this section) is simply a post-occupancy verification of design objectives and is an integral part of a sustainable building.

Because the focus of this text is on construction and materials, the requirements for Materials and Resources category are given in greater detail in the chapter.

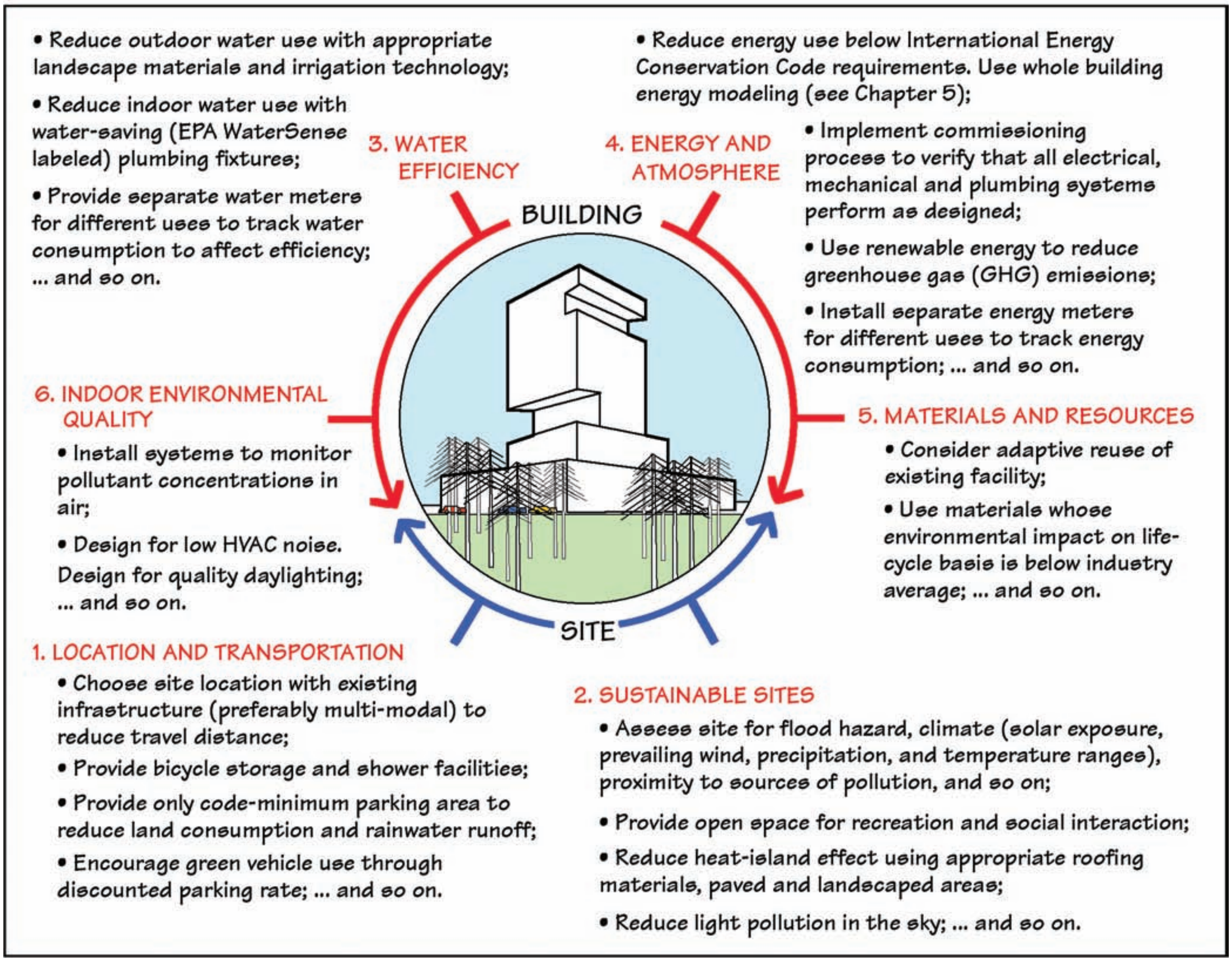

• Reduce outdoor water use with appropriate landscape materials and irrigation technology;
• Reduce indoor water use with water-saving (EPA WaterSense labeled) plumbing fixtures;
• Provide separate water meters for different uses to track water consumption to affect efficiency; ... and so on.
3. WATER EFFICIENCY
BUILDING
4. ENERGY AND ATMOSPHERE
• Reduce energy use below International Energy Conservation Code requirements. Use whole building energy modeling (see Chapter 5);
• Implement commissioning process to verify that all electrical, mechanical and plumbing systems perform as designed;
• Use renewable energy to reduce greenhouse gas (GHG) emissions;
• Install separate energy meters for different uses to track energy consumption; ... and so on.
6. INDOOR ENVIRONMENTAL QUALITY
• Install systems to monitor pollutant concentrations in air;
• Design for low HVAC noise. Design for quality daylighting; ... and so on.
5. MATERIALS AND RESOURCES
• Consider adaptive reuse of existing facility;
• Use materials whose environmental impact on life-cycle basis is below industry average; ... and so on.
SITE
1. LOCATION AND TRANSPORTATION
• Choose site location with existing infrastructure (preferably multi-modal) to reduce travel distance;
• Provide bicycle storage and shower facilities;
• Provide only code-minimum parking area to reduce land consumption and rainwater runoff;
• Encourage green vehicle use through discounted parking rate; ... and so on.
2. SUSTAINABLE SITES
• Assess site for flood hazard, climate (solar exposure, prevailing wind, precipitation, and temperature ranges), proximity to sources of pollution, and so on;
• Provide open space for recreation and social interaction;
• Reduce heat-island effect using appropriate roofing materials, paved and landscaped areas;
• Reduce light pollution in the sky; ... and so on.

FIGURE 10.4 Important elements of a sustainable building, separated into two parts: (a) sustainability considerations with respect to site and (b) sustainability considerations with respect to building.

LEED v4

As shown in Figure 10.2, the LEED rating system has gone through a number of updates and refinements over the years. Each update is given a version number. The latest update is version 4 (called *LEED v4*), which was published toward the end of 2013, becoming effective three years later in order to provide time to architects, engineers, and constructors to become familiar with the updates from LEED v3.

Because different types of development pose different sustainability challenges, there are several variations in the LEED v4 rating system. These rating systems are:

1. LEED v4 BD+C (for building design and construction)
2. LEED v4 O+M (for operation and maintenance of existing buildings to improve their impact on the environment by selecting sustainable equipment)
3. LEED v4 ID+C (for interior design and construction to improve tenant facilities)
4. LEED v4 BD+C (for design and construction of new homes and multifamily midrise)
5. LEED v4 ND (for neighborhood development)

LEED v4 FOR BUILDING DESIGN AND CONSTRUCTION (BD+C) Rating System 1 (LEED v4 BD+C), which applies to new buildings and major renovations, is the most commonly sought rating system, and is further subdivided by USGBC into seven types, based on the building's use—schools, healthcare, hospitality, data centers, and so on, Figure 10.5. The sustainability of a building belonging to any one of these seven types is based on its performance with respect to all six impact categories shown in Figure 10.4.

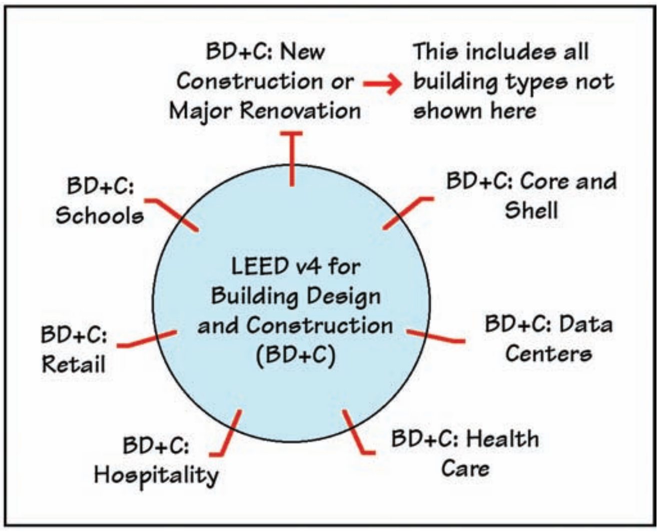

BD+C: New Construction or Major Renovation
This includes all building types not shown here
BD+C: Schools
BD+C: Core and Shell
LEED v4 for Building Design and Construction (BD+C)
BD+C: Retail
BD+C: Data Centers
BD+C: Hospitality
BD+C: Health Care

FIGURE 10.5 Seven rating systems in LEED v4 Building Design and Construction (BD+C).

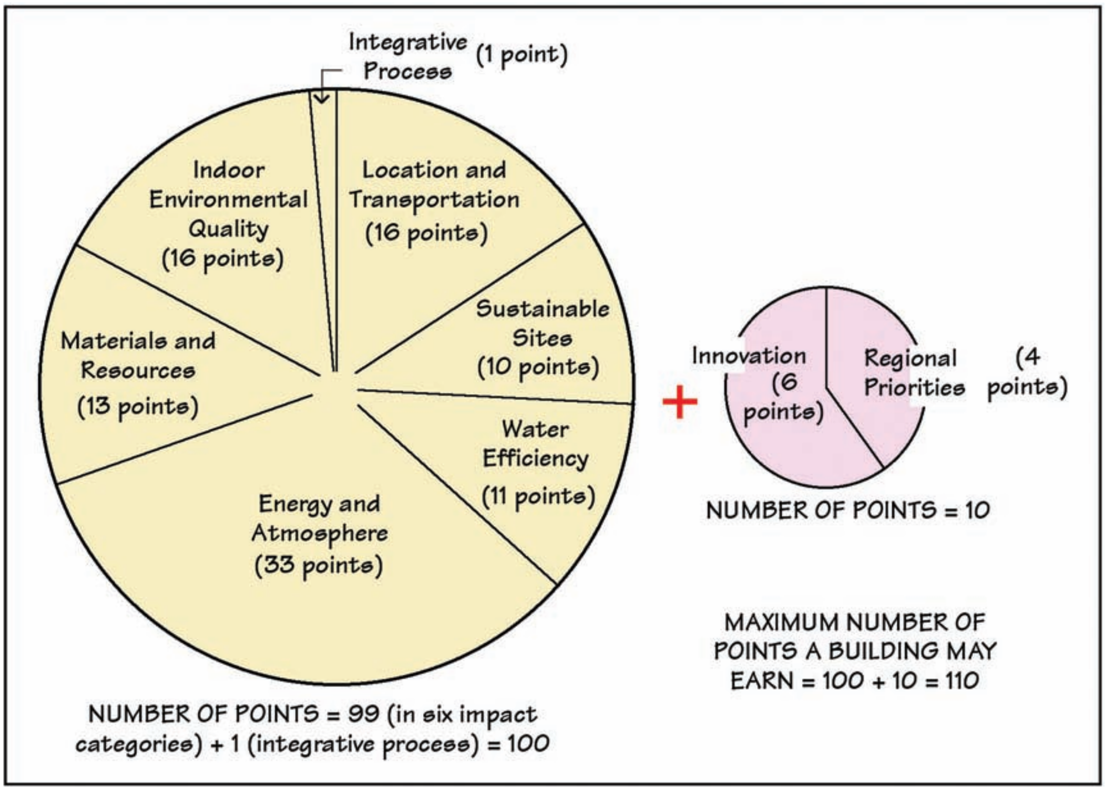


FIGURE 10.6 Maximum points admissible in various categories in LEED BD+C rating system for new construction or major renovations.

Each impact category has been assigned points based on its importance to building's sustainability, Figure 10.6. The total number of points assigned to all six impact categories is 99. The category representing energy and atmosphere has been assigned the largest number of points (33 points out of 99), which signifies its relative importance. The points assigned to a category represent the maximum points a building may earn in that category.

There are a few additional categories that can add to the total number of points a building may score. The category Integrative Process (IP), which is not an impact category, is assigned one point so that total number of points in seven categories (including IP) is 100, as shown in Figure 10.6. In addition to the points assigned to seven categories, there are two miscellaneous categories.

a. Innovation (IN) with 6 points
b. Regional priorities (RP) with 4 points

Together, IN and RP may earn 10 points, so that the maximum number of points a building may earn is 110. A discussion of IP, IN, and RP, giving their contributions to the rating system, is provided in the following paragraphs.

The sustainability rating of a building is determined by the sum of all points it scores, and the total score determines the *LEED certification level*. Four levels of sustainability are recognized by LEED v4 BD+C, as listed here and illustrated in Figure 10.7.

a. Certified (40 to 49 points)
b. Silver (50 to 59 points)
c. Gold (60 to 79 points)
d. Platinum (80 to 110 points), Figure 10.7.

A building earning ≤39 points is not considered a green building per the LEED-rating system.

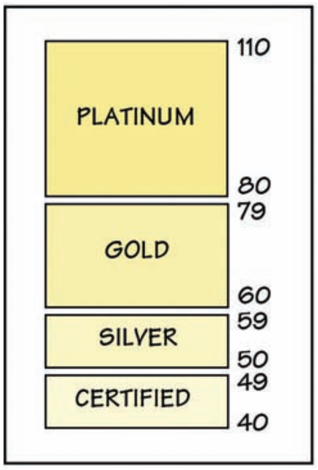


FIGURE 10.7 Number of points required for a building to qualify for various certification levels in LEED v4.

Integrative Process (IP) The integrative process (IP) is a process of obtaining collective input of all stakeholders in the project (owner, architect, contractor, landscape architect, and various engineering consultants) before the schematic design stage. The process typically involves considering climate, building orientation, site conditions, landscape features, building envelope considerations, etc., with the end goal of obtaining a conceptual design framework that conserves energy, water, and material resources, and optimizes building areas and volumes.

Typically, the IP would require a preliminary analysis of massing, building form and geometry, orientation, shading devices, exterior envelope (particularly window-to-wall ratios), ratio of hard-to-soft landscape, strategies for rainwater harvesting, etc. Energy modeling analyses on various “simple-box” massing alternatives would be undertaken at this stage.

Although this approach is one that the architects are quite familiar with, the difference is that in the traditional approach, architects do not generally involve other stakeholders, or involve just a few important ones. In the IP approach, the input of all stakeholders is required to ensure that nothing has been overlooked and each team member has provided the expert input through individual and integrated research, and design charrette. The IP approach should culminate into broad-based decision making that forms the basis of schematic design in which all stakeholders have the joint authorship.

Innovation (IN) Sustainable building design is in its early stages, and much of it is still evolving. Several sustainable strategies are yet to be uncovered. In recognition of this fact, the LEED rating system permits earning points for significant and measurable sustainable performance not addressed in the rating system. The innovation can be a part of a recognized impact category or outside of it.

Regional Priorities (RP) Various environmental concerns have different importance in different regions. Water resource management in a region where annual rainfall is low is of high priority as compared with a region that receives plentiful rainfall. If greenhouse gas emissions in a region are high, green energy and (or) optimizing energy performance will have a high priority in that region. USGBC gives a list of six regional priorities for every U.S. locations using a click-on-the-map, GIS-based system. For example, optimizing energy performance, rainwater management, and indoor water use reduction are among the RPs for Los Angeles, California.

OVERALL COMMISSIONING AUTHORITY

To ensure that the building’s pre-occupancy performance is as intended and designed (with respect to energy use, envelope design, water use, waste management, indoor air quality, etc.), the LEED rating system recommends that the building be commissioned. *Commissioning* is a systematic, post-occupancy evaluation to verify that the basic building components and systems have been installed and calibrated to function as intended.

Engaging an independent *commissioning authority* (also called a *commissioning agent*) is a mandatory LEED requirement to help the owner obtain an objective evaluation of the design and construction team’s work. Engaging a commissioning authority early in the project-delivery process (preferably during the design phase) ensures that the postcompletion verification strategies used by the authority are clear to the design and construction teams.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The embodied energy in a building is a measure of the energy consumed
   a. to extract raw materials from the earth and manufacture a finished building product.
   b. in the administrative functions related to product manufacturing.
   c. to transport the finished product to the building site and install it in the building.
   d. all of the above.
   e. (a) and (c) only.

2. Architects generally did not consider the effect of the natural environment on buildings prior to the environmental revolution begun in the early 1970s.
   a. True
   b. False

3. One of the major U.S. organizations that deals with sustainable architectural design is
   a. USEBC.
   b. USFBC.
   c. USGBC.
   d. USHBC.
   e. none of the above.

4. BREEAM is a building sustainability rating system, which originated in the United Kingdom.
   a. True
   b. False

5. Which is the latest version of LEED as given in this text?
   a. LEED v2
   b. LEED v3
   c. LEED v4
   d. LEED v5
   e. None of the above

6. The total number of environmental impact categories in the latest version of LEED BD+C rating system, as given in this text, is
   a. 5.
   b. 7.
   c. 9.
   d. 10.
   e. none of the above.

7. The total number of points assigned to all impact categories (excluding, IP, IN, and RP) in LEED v4 BD+C is
   a. 80.
   b. 90.
   c. 100.
   d. 110.
   e. none of the above.

8. The environmental impact category in LEED BD+C to which the greatest number of points have been assigned is
   a. Materials and Resources.
   b. Water Efficiency.
   c. Sustainable Sites.
   d. Energy and Atmosphere.
   e. Indoor Environmental Quality.

9. In the process of pursuing LEED rating for a project, the role of category—Integrative Process (IP)—comes
   a. before or during schematic design phase.
   b. during design development phase.

c. during construction document phase.
d. during construction phase.
e. during postconstruction phase.

10. Per LEED BD+C rating system, a building may receive recognition as a green building at the following levels.
a. Platinum, Gold, Silver, and Bronze
b. Gold, Silver, Bronze, and Certified
c. Gold, Silver, and Bronze
d. Gold, Silver, and Merit
e. Platinum, Gold, Silver, and Certified

11. A building that receives a total score of 55 points in the LEED–NC rating system is recognized at
a. Sustainable level.
b. Certified level.
c. Silver level.
d. Gold level.
e. Green level.

12. The maximum number of points a building may earn in LEED BD+C rating system is
a. 100.
b. 75.
c. 50.
d. 25.
e. none of the above.

13. The process of commissioning of a building occurs
a. before or during schematic design phase.
b. during design development phase.
c. during construction document phase.
d. during construction phase.
e. during postconstruction phase.

14. The terms "commissioning authority" and "commissioning agent" mean the same.
a. True
b. False

10.4 ATTRIBUTES OF SUSTAINABLE BUILDING MATERIALS

Because building materials constitute a large part of the environmental burden created by a building, the use of green building materials and products is one of the several factors that make a building sustainable. Extracting materials from the earth and processing them into a finished product require energy and water resources and produce waste, some of which may be hazardous. Some products give off toxic gases after installation, called *off-gassing*. Others require cleaning with chemicals that may do likewise. Post-consumer disposal of products consumes landfills, some of which may pollute groundwater.

Materials whose overall environmental burden is low are referred to as *green materials*. More specifically, the greenness (sustainability) of a product is a function of the following attributes:

1. Renewability—distinction between renewable and nonrenewable materials
2. Local production—definition of locally extracted and manufactured materials
3. Recyclability—amount of recycled content
4. Recovery and reusability
5. Impact on the environment caused by material production—environmental product declaration (EPD)
6. Material ingredients of products—health product declarations (HPD)

The attributes listed above form the basis of LEED v4 Materials and Resources Category and comprise a total of 13 points, as shown in Figure 10.6. They are described in detail in the following sections. Sustainability attributes 1 to 4 are covered first, followed by the coverage of attributes 5 and 6.

10.5 MATERIAL SUSTAINABILITY ATTRIBUTES 1 TO 4—RENEWABILITY, LOCAL PRODUCTION, RECYCLABILITY, AND RECOVERY AND REUSABILITY

The *law of conservation of matter* states that all matter on the earth and within its atmosphere can neither be destroyed nor be created. In other words, whatever existed on the earth at the dawn of time will always exist. Its physical or biological state may, however, change through natural or human-made processes. The basic elements of which a material is composed continue to exist forever on the earth or in its atmosphere. For example, when iron corrodes, it becomes iron oxide. The amounts of iron and oxygen on the earth remain unchanged in this transformation.

The transformation of matter (contained within both physical and biological realms) from one state to the other, and in various combinations, is cyclical. In other words, matter cycles back and forth within physical realms and also from the physical to biological realms.

For example, there is a constant amount of water on the earth, held within the oceans, in the atmosphere, and in other terrestrial entities—both living and nonliving. The processes of evaporation, condensation, consumption, and disposal of water simply move it from one state to another and from one realm to another. There may be drought in one region and excessive rainfall in another region, but the total quantity of water on the earth and in its atmosphere remains constant.

SUSTAINABLE MATERIALS ATTRIBUTE 1: RENEWABILITY

The preceding discussion shows that all materials are theoretically renewable. However, some materials renew over a short-duration cycle, whereas the cycles of others are long. For some materials, the cycle may extend over millions of years. Materials that have a short renewal cycle (comparable with human lifespan) and require limited processing input to convert them to a usable form are referred to as *renewable materials*. Conversely, materials that have long renewal cycles and require large processing input are called *nonrenewable materials*. A renewable material is greener than a nonrenewable material.

The renewal cycle of most tree species used in construction is brief—usually 25 to 50 years. To transform trees into wood products requires a small amount of additional resources. Wood is, therefore, a renewable material. Perhaps one of the most renewable building materials is adobe. We can dig earth from the ground, shape it into (sundried clay) adobe bricks, and construct buildings with them with a negligible amount of processing. When an adobe building is no longer needed, it can be demolished, and its material can be reprocessed for use in a different building with zero renewability duration. Alternatively, the material may be returned to the earth in almost the same state in which it was first obtained.

Metals, stone, glass, and plastics are examples of nonrenewable materials because they take much longer to renew and require excessive processing resources to convert them into usable states, Figure 10.8. Take the example of iron again. If left unprotected, it rusts. Rust is essentially the same as iron ore but in a highly diluted form. To obtain iron from the rust, which by mingling with the other constituents of the earth's surface, becomes further diluted in iron concentration (i.e., becomes a low-grade iron ore), requires enormous processing energy. It also produces enormous waste and pollution. Natural geological processes can provide iron ore with a high iron concentration, but these processes take millions of years.

BIO-BASED MATERIALS AND LANDFILLS—WASTE MUST EQUAL FOOD

Wood and wood-based products (disregarding the small amount of adhesives used in engineered wood products, such as plywood) also happen to be biodegradable. Therefore, building product packaging, if required, consisting of paper-based products is preferred. Ideally, all waste sent to landfills should be biodegradable and nontoxic so that it becomes food for plants and other living creatures. Some ecologists have coined the axiom: *Waste must equal food*. Waste that cannot be converted to a biodegradable material should be recycled over and over again.

The Material and Resource (MR) impact category in LEED v4 recognizes the use of bio-based materials, such as wood products, for earning credits, Figure 10.9. The wood used in these products, however, must be certified by Forest Stewardship Council (see Section 10.9).

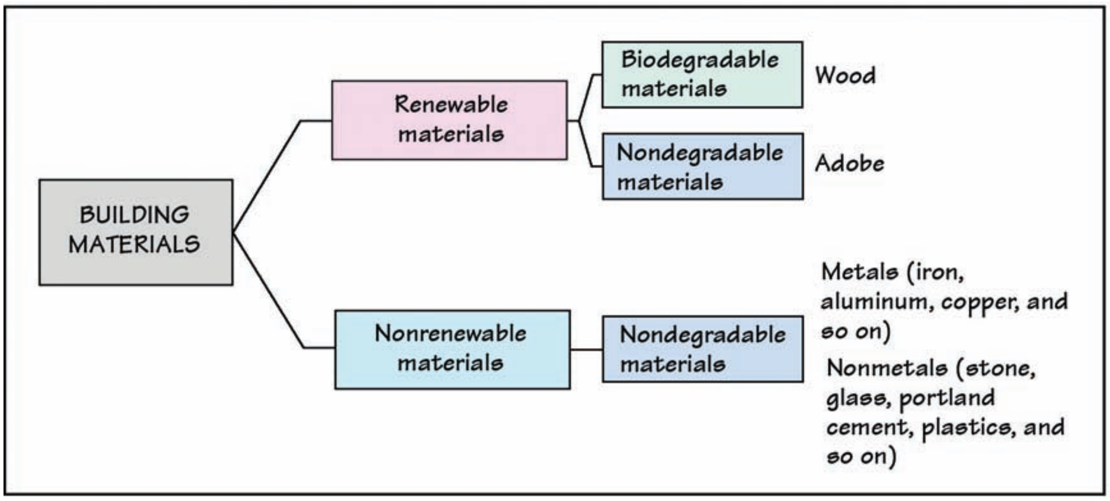
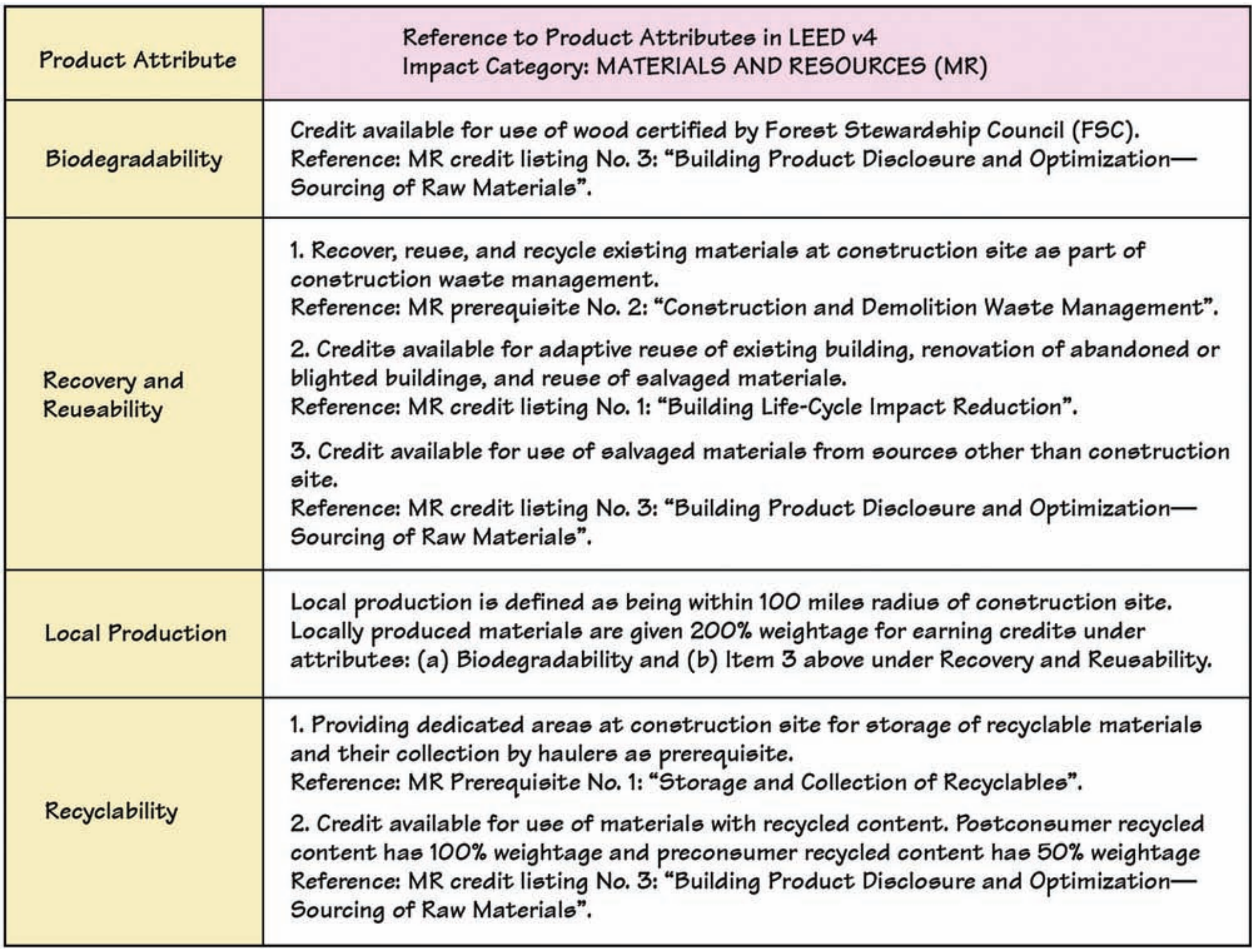


FIGURE 10.8 Renewable, nonrenewable, and biodegradable building materials.



Product Attribute	Reference to Product Attributes in LEED v4 Impact Category: MATERIALS AND RESOURCES (MR)
Biodegradability	Credit available for use of wood certified by Forest Stewardship Council (FSC). Reference: MR credit listing No. 3: "Building Product Disclosure and Optimization—Sourcing of Raw Materials".
Recovery and Reusability	1. Recover, reuse, and recycle existing materials at construction site as part of construction waste management. Reference: MR prerequisite No. 2: "Construction and Demolition Waste Management". 2. Credits available for adaptive reuse of existing building, renovation of abandoned or blighted buildings, and reuse of salvaged materials. Reference: MR credit listing No. 1: "Building Life-Cycle Impact Reduction". 3. Credit available for use of salvaged materials from sources other than construction site. Reference: MR credit listing No. 3: "Building Product Disclosure and Optimization—Sourcing of Raw Materials".
Local Production	Local production is defined as being within 100 miles radius of construction site. Locally produced materials are given 200% weightage for earning credits under attributes: (a) Biodegradability and (b) Item 3 above under Recovery and Reusability.
Recyclability	1. Providing dedicated areas at construction site for storage of recyclable materials and their collection by haulers as prerequisite. Reference: MR Prerequisite No. 1: "Storage and Collection of Recyclables". 2. Credit available for use of materials with recycled content. Postconsumer recycled content has 100% weightage and preconsumer recycled content has 50% weightage Reference: MR credit listing No. 3: "Building Product Disclosure and Optimization—Sourcing of Raw Materials".

FIGURE 10.9 Building product attributes (biodegradability, recovery and reusability, local production, and recyclability) and their references for earning credits in Impact Category: Materials and Resources (MR) of LEED v4.

SUSTAINABLE MATERIALS ATTRIBUTE 2: LOCAL PRODUCTION

Use of local materials is obviously a sustainable attribute because it saves on energy use in transportation. In LEED v4 rating system, "local material" is defined as one whose entire manufacturing chain (from raw material extraction to finished product) lies within 100-mile radius of the construction site, and is recognized as a creditable attribute in Materials and Resource (MR) impact category, as shown in Figure 10.9.

SUSTAINABLE MATERIALS ATTRIBUTE 3: MATERIAL RECYCLABILITY

The greater the amount of recycled content in a material, the greener it is. Recycling is classified into two types:

a. Pre-consumer recycling (also called *internal recycling*)
b. Post-consumer recycling (also called *external recycling*)

Pre-consumer recycling is the reuse of materials that are byproducts or waste products from manufacturing, and have not left the manufacturing facility, Figure 10.10. The brick- and glass-manufacturing industries and several others have used internal recycling for a long time. Broken or defective bricks or glass are reused as raw materials in the manufacturing process. Ready-mix concrete manufacturing plants recycle wastewater reclaimed from washing concrete mixers after they return for recharge and delivery.

Post-consumer recycling, on the other hand, is reclaiming a material for use in the manufacturing process of the same or a different product after it has become obsolete or unnecessary in its present application. For example, concrete obtained from a demolished building can be crushed and used as a drainage layer under a new concrete slab-on-grade in place of crushed stone. In some cases, crushed old concrete may be used as coarse aggregate in new concrete. Similarly, reinforcing or structural steel recovered from a demolished building, or old automobiles, can be melted and processed as new steel (see Figure 18.8). Both these are examples of post-consumer recycling.

An increasingly larger number of products are being manufactured with post-consumer recycled materials, and their recycled content is also increasing. Consequently, recycling has become a major and diverse industry that employs a large number of skilled and unskilled workers.

NOTE

Difference Between Renewal and Recycling

The difference between the renewal and recycling of a material is subtle. *Renewal* refers to the process of recycling that occurs in nature. *Recycling* is a deliberate process.

Pre-consumer Recycled Content versus Post-consumer Recycled Content Most materials contain both—pre-consumer recycled content and post-consumer recycled content. Because post-consumer recycling is in fact waste recycling, it contributes more to the sustainability of a product than pre-consumer recycled content. In LEED v4 (Materials and Resource impact category), post-consumer recycled content in a material is given 100% weightage, while pre-consumer recycled content is assigned 50% weightage, as shown in Figures 10.9 and 10.10.

Sustainable Materials Attribute 4: Material Recovery and Reusability

An effective way of greening a building is by using materials that have been recovered (salvaged) from the demolition of existing buildings. This reduces raw-material extraction and also reduces the burden on landfills. Obviously, salvaged materials must be obtained from nearby sources—within 100 miles from the construction site. The Material and Resource (MR) impact category in LEED v4 recognizes the use of recovered materials, as shown in Figure 10.9.

The salvaged materials must be of usable quality, and their remaining life spans must meet the requirements of their reuse. The economics of recovery and reuse are more favorable with durable materials, such as bricks, natural stone, steel, and aluminum, than with materials with short life spans.

It is expected that as the use of salvaged materials becomes an accepted part of building design and construction practices, demolition recovery will become a more important commercial enterprise. The role of manufacturers in this area cannot be overemphasized. As the manufacturing industry moves further toward sustainability and assumes responsibility for the entire life cycle of the materials it produces, recovery and reuse could become part of the manufacturers' responsibilities, that is, *cradle-to-grave responsibility*.

In this scenario, the manufacturer retains ownership of the product, which is transferred to the consumer for only a certain period. At the end of that period, the take-back of the product by its manufacturer is mandated, for refurbishing, remanufacturing, or recycling as needed. The ultimate disposal of the product in a landfill also remains the manufacturer's responsibility. This should make product manufacturing and its use in buildings approach an ideal closed-loop system, Figure 10.11.

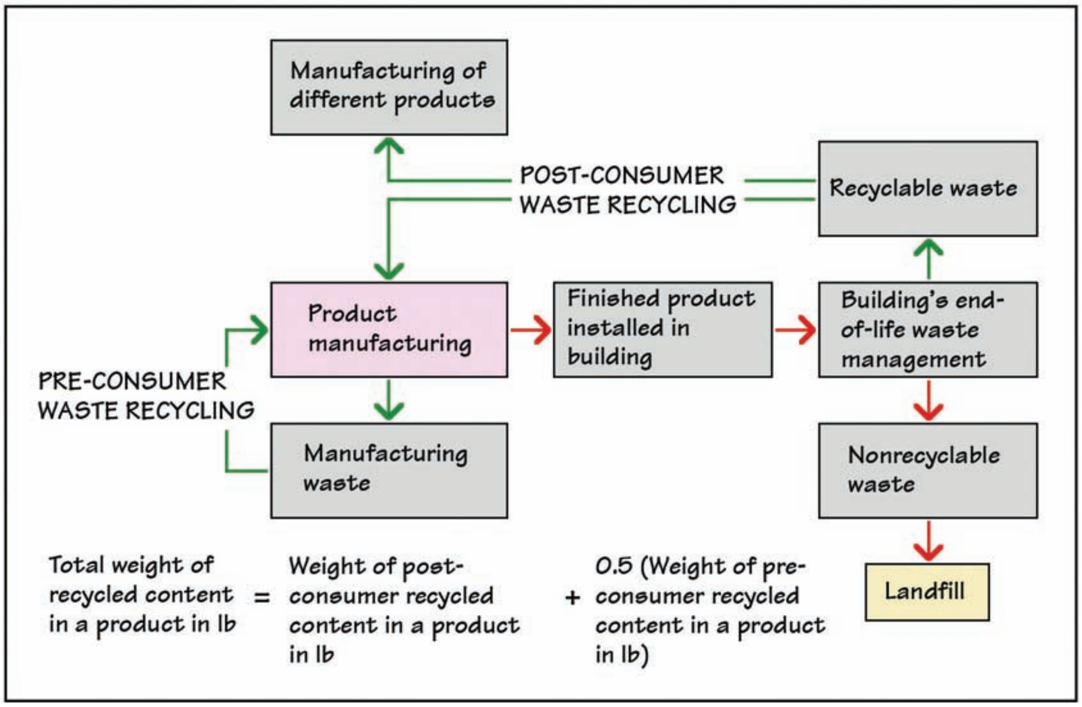

Manufacturing of different products
POST-CONSUMER WASTE RECYCLING
Recyclable waste
Product manufacturing
Finished product installed in building
Building's end-of-life waste management
PRE-CONSUMER WASTE RECYCLING
Manufacturing waste
Nonrecyclable waste
Total weight of recycled content in a product in lb = Weight of post-consumer recycled content in a product in lb + 0.5 (Weight of pre-consumer recycled content in a product in lb)
Landfill

FIGURE 10.10 Difference between pre-consumer waste recycling and post-consumer waste recycling. Per LEED v4, pre-consumer waste used in a project carries half the weightage of post-consumer waste.

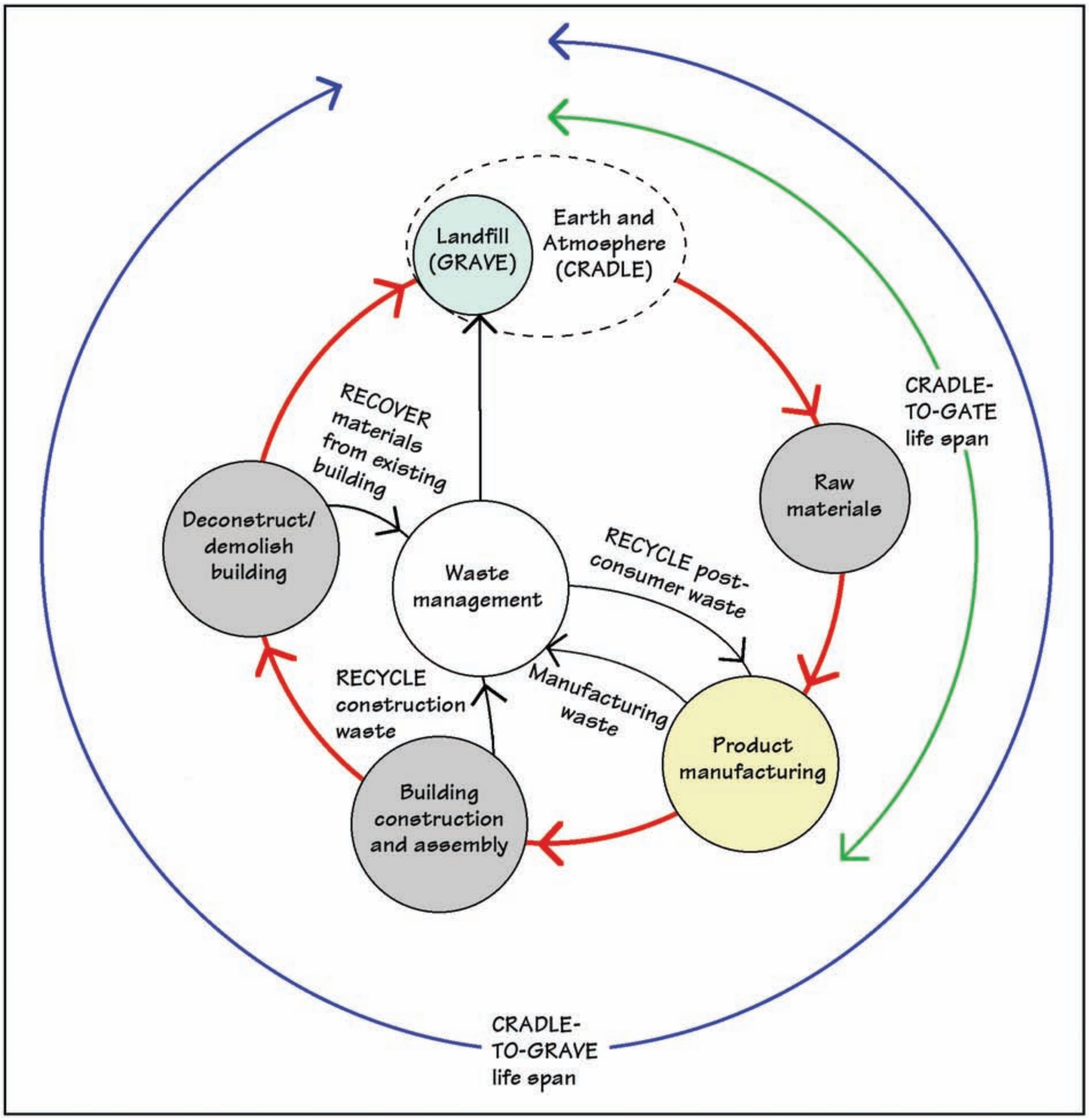

Landfill (GRAVE)
Earth and Atmosphere (CRADLE)
CRADLE-TO-GATE life span
Raw materials
RECOVER materials from existing building
Deconstruct/ demolish building
Waste management
RECYCLE post-consumer waste
Product manufacturing
Manufacturing waste
RECYCLE construction waste
Building construction and assembly
CRADLE-TO-GRAVE life span

FIGURE 10.11 A building product's lifecycle, showing important stages of its life, and highlighting the distinction between cradle-to-gate and cradle-to-grave life spans. The term "gate" means factory gate and the term "grave" usually means the landfill. The term "cradle-to-cradle" is an ideal life cycle, in which the product is recycled multiple times and disposed of only when it is benign to the environment.

As environmental legislation makes waste management and disposal more costly, manufacturers will be increasingly forced to make their products greener. Removing hazardous contents, if any, before disposal and ensuring rapid degradability of materials (e.g., computers, furniture, or carpets) in landfills will be the manufacturers' responsibility.

10.6 MATERIAL SUSTAINABILITY ATTRIBUTE 5—ENVIRONMENTAL PRODUCT DECLARATIONS (EPD)

The making of building materials has a negative impact on the environment because the manufacturing process emits greenhouse gases, causes global warming, consumes energy and other resources, and so on. Therefore, an extremely important evaluation of a material's sustainability is obtained by assessing its impact on the environment, referred to as the *environmental burden*. The lower the burden, the greener is the material.

NOTE

Reduce, Reuse, and Recycle—Three Tenets of Sustainability

Reduce, reuse, and recycle are considered to be the three most important tenets of sustainable construction. These tenets are listed in order of their importance. The first tenet (reduce), in fact, far outweighs the other two in importance.

Reduction Tenet Sadly Ignored in Sustainability Rating Systems

As discussed, a great deal of stress is currently being placed on reusability and recyclability in a sustainability rating system. The same level of concern is, however, lacking toward appropriate sizing of buildings, automobiles, and other items of human consumption. Regardless of how successful we are with reusability and recyclability, sustainability will not be achieved without seriously addressing the *reduction* tenet.

A worrying statistic about buildings is the gradual increase in the average size of new homes built in the United States during the past several decades. In 1970, a typical new house was 1,500 sq ft. In 2005, the corresponding size was 2,300 sq ft—an increase of approximately 50%. At the same time, the average family size has declined [Ref. 10.5].

The environmental parameters negatively impacted by a material are several. However, LEED v4 lists following six parameters to be considered in determining the impact of a material on the environment:

- **i.** Global warming potential
- **ii.** Ozone depletion in earth's stratosphere
- **iii.** Acidification of land and water sources
- **iv.** Eutrophication
- **v.** Ozone formation in earth's troposphere
- **vi.** Depletion of nonrenewable energy sources

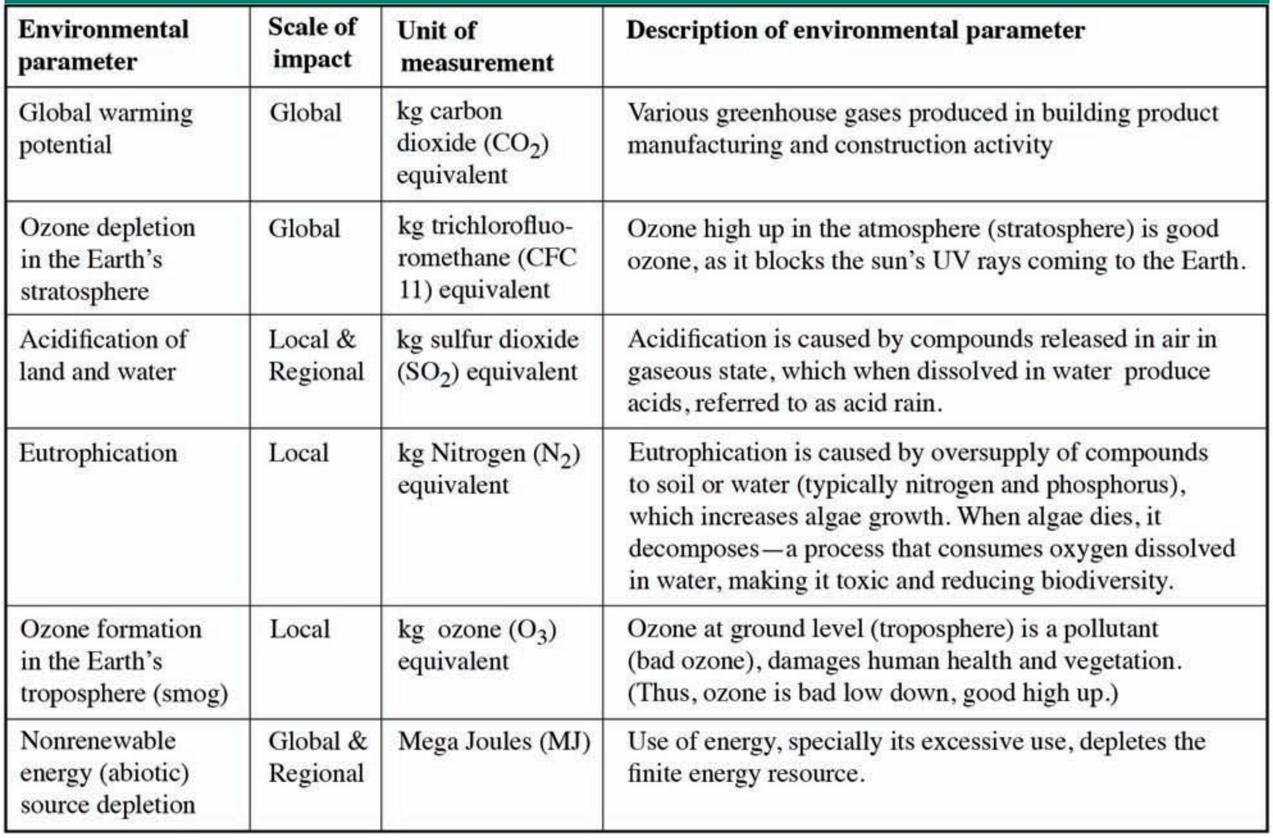
The impact from each parameter is measured in different units and the unit for each parameter is normalized to apply to all situations related to that parameter, that is, a common measuring unit is used for that parameter. For example, in the manufacturing of a material different types of greenhouse gases—carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (NO_2), etc.—are emitted. The global warming potential (GWP) of each gas is not the same. Therefore, a common unit—CO_2 equivalent—is used for measuring GWP from various greenhouse gases. Table 10.1 lists the six environmental parameters along with a brief explanation of each parameter, and their measurement units.

ENVIRONMENTAL IMPACT—THE MATERIAL'S ENVIRONMENTAL PRODUCT DECLARATIONS (EPD)

The environmental impact of a material, enumerated for all six parameters listed above, is called *environmental product declarations*, EPD, which can be either cradle-to-gate EPD or cradle-to-grave EPD, Figure 10.12. Cradle-to-gate EPD includes the consideration of environmental impact beginning with raw material extraction, transportation of raw materials to factory, and finally, the manufacturing of the product and its packaging (see Figure 10.11). The term "gate" in cradle-to-gate implies factory gate.

Cradle-to-grave EPD includes consideration of cradle-to-gate EPD plus EPD (i.e., environmental impact) related to transportation of product from factory gate to construction site, its installation in the building including construction waste, reuse, if any, after the building is demolished, and its final disposal to a landfill. Because the EPD is provided by material manufacturers, cradle-to-gate EPD is more readily available and is commonly used.

TABLE 10.1 ENVIRONMENTAL PARAMETERS CONSIDERED IN DETERMINING THE EPD OF A BUILDING MATERIAL



Environmental parameter	Scale of impact	Unit of measurement	Description of environmental parameter
Global warming potential	Global	kg carbon dioxide (CO_2) equivalent	Various greenhouse gases produced in building product manufacturing and construction activity
Ozone depletion in the Earth's stratosphere	Global	kg trichlorofluoromethane (CFC 11) equivalent	Ozone high up in the atmosphere (stratosphere) is good ozone, as it blocks the sun's UV rays coming to the Earth.
Acidification of land and water	Local & Regional	kg sulfur dioxide (SO_2) equivalent	Acidification is caused by compounds released in air in gaseous state, which when dissolved in water produce acids, referred to as acid rain.
Eutrophication	Local	kg Nitrogen (N_2) equivalent	Eutrophication is caused by oversupply of compounds to soil or water (typically nitrogen and phosphorus), which increases algae growth. When algae dies, it decomposes—a process that consumes oxygen dissolved in water, making it toxic and reducing biodiversity.
Ozone formation in the Earth's troposphere (smog)	Local	kg ozone (O_3) equivalent	Ozone at ground level (troposphere) is a pollutant (bad ozone), damages human health and vegetation. (Thus, ozone is bad low down, good high up.)
Nonrenewable energy (abiotic) source depletion	Global & Regional	Mega Joules (MJ)	Use of energy, specially its excessive use, depletes the finite energy resource.

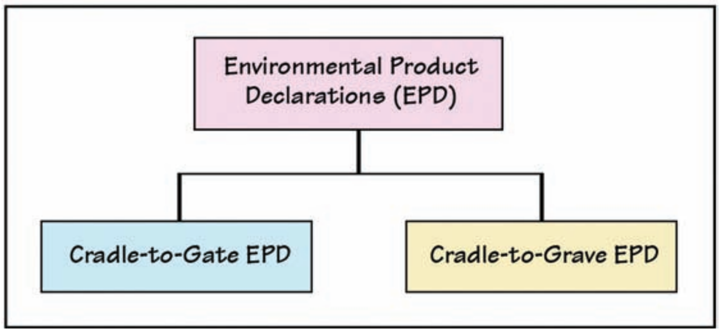

Environmental Product Declarations (EPD)
Cradle-to-Gate EPD
Cradle-to-Grave EPD

FIGURE 10.12 Environmental product declarations (EPD) may be cradle-to-gate EPD or cradle-to-grave EPD.

The cradle-to-gate EPD, as provided ("declared") by the manufacturers, can be of three types, illustrated in Figure 10.13 and described hereunder.

i. Product-specific, self-declared EPD, prepared by the manufacturer without an independent, third-party validation, referred to as *ISO Type II EPD*.
ii. Industry-wide generic EPD of a product, prepared by an independent, third-party EPD program operator. Such an EPD is called *ISO Type III EPD*. Table 10.2 gives the details of generic EPD of a $\frac{5}{8}$-in. Type X gypsum board (see Section 16.5 for explanation of Type X gypsum board).
iii. Product-specific EPD, prepared by an independent, third party, which is also an ISO Type III EPD.

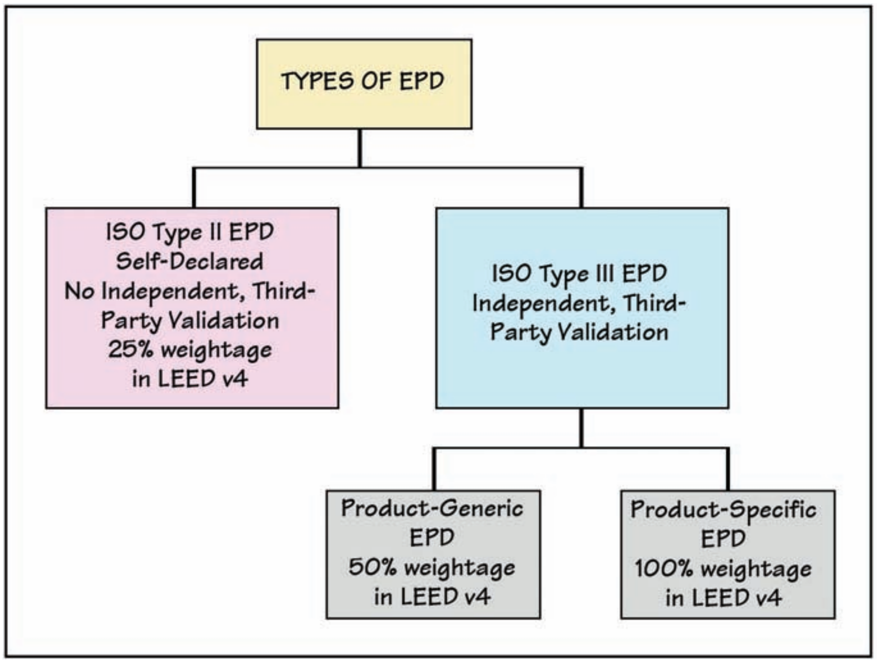

TYPES OF EPD
ISO Type II EPD
Self-Declared
No Independent, Third-Party Validation
25% weightage
in LEED v4
ISO Type III EPD
Independent, Third-Party Validation
Product-Generic EPD
50% weightage
in LEED v4
Product-Specific EPD
100% weightage
in LEED v4

FIGURE 10.13 Types of EPD and their weightages in LEED v4. ISO is a short name (not an acronym) for International Organization for Standardization.

TABLE 10.2 CRADLE-TO-GATE EPD OF A TYPICAL $\frac{5}{8}$-IN.-THICK, TYPE X GYPSUM BOARD (QUANTITY 1,000 SQ FT)

Environmental parameter	Global warming potential	Stratospheric ozone depletion	Acidification of land and water	Eutrofication	Tropospheric ozone formation	Abiotic depletion
Magnitude of environmental impact	317.4	$(1.9)10^{-5}$	2.46	0.37	12.41	596.1
Measurement unit	kg CO_2 eq	kg CFC 11 eq	kg SO_2 eq	kg N_2 eq	kg O_3 eq	MJ

Note that *ISO Type I EPD* is not an EPD, but simply an Eco label based on one or two aspects of sustainability, discussed in Section 10.9.

An EPD program operator is an organization specialized in preparing ISO Type III EPD. A few prominent EPD program operators in the United States are Underwriters Laboratory's (UL) Environment Inc. (ULE), ASTM International, and Institute for Environmental Research and Education (IERE). ISO is an acronym for International Organization for Standardization, previously known as International Standards Organization.

EPD of Materials in LEED v4

LEED v4 places a great deal of emphasis on EPD in Materials and Resources (MR) impact category by assigning a relatively large chunk of points (5 out of 13 points) to be earned by demonstrating reduced environmental impact through EPD information. Product-specific ISO Type III EPD is weighted 100%, ISO Type III (generic) EPD is weighted 50%, and ISO Type II is weighted 25%, as shown in Figure 10.13.

EPD Analysis and Interpretation

As Table 10.2 shows, an EPD is similar to a label on food packages that lists the amounts of sugar, saturated fat, unsaturated fat, calories, etc. The label does not describe the food as good or bad, as that decision must be left to the consumer. Similarly, EPD information does not include how environmentally good or bad the product is; that interpretation is the responsibility of the design team.

The EPD of a construction assembly can be obtained by aggregating the EPD information of various components of the assembly. For example, the EPD of an interior partition consisting of cold-formed steel CFS) studs and gypsum board on both sides can be obtained by adding the EPD information of gypsum board and studs. It is hoped that the EPD of commonly used assemblies will be provided by the manufacturers in the same way as they currently provide other performance data, such as fire resistance, sound transmission loss, load-carrying capacity, and so on.

The EPD of a product is only comparable with another similar or substitute product. Thus, comparing the EPD of 100 sq ft of ceramic floor tiles with 100-sq ft vinyl floor tiles or with 100 sq ft of terrazzo flooring is acceptable. However, comparing the EPD of gypsum wallboard with that of floor tiles is meaningless. Similarly, the EPD of one type of exterior wall assembly (e.g., a steel-stud assembly clad with brick veneer) can be compared with a different type of exterior wall assembly (e.g., a steel-stud or wood-stud assembly clad with stucco). Comparing the EPD of an exterior wall assembly with a roof assembly is pointless.

EPD—Benefits and Their Future

EPD are not only beneficial for architectural decision making but also to the industry because the preparation of an EPD requires intimate details of the manufacturing process, from raw materials extraction to the packaging of the finished product. This produces deep insight into the manufacturing process, which can be used as an internal control instrument by the industry to increase manufacturing efficiency while reducing environmental impact. As building sustainability becomes commonplace through a widespread adoption of International Green Construction Code, the architectural profession will be demanding the submission of EPD of products and assemblies from contractors at the time of bidding.

10.7 MATERIAL SUSTAINABILITY ATTRIBUTE 6—HEALTH PRODUCT DECLARATIONS (HPD)—THE MATERIAL INGREDIENTS

While the EPD of a product is a measure of the impact of the product on the environment, the health product declaration is a measure of the impact of that product on human health. An HPD of a product is a full disclosure of the entire inventory of chemical compounds in the product and their effect on health. As previously stated, an EPD is similar to the label on a food package listing the amount of sugar, calories, various types of fats, etc. present in that food. An HPD is similar to the information given on a food package that lists all the ingredients and their amount used in preparing that food item.

Building product manufacturers are quite familiar with the requirement of disclosing information regarding the safety hazard the product poses to construction workers through the document called *material safety data sheet* (MSDS). While the purpose of an MSDS is to inform the workers of occupational safety in working with the product, the purpose of an

HPD is to give information on the product's impact on human health due to its presence in the building.

The preparation of the HPD of a product is based on HPD Open Standard managed by HPD Collaborative. LEED v4 requires HPD information under "Building Product Disclosure and Optimization: Material Ingredients" in Materials and Resources (MR) impact category.

10.8 CRADLE-TO-CRADLE (C2C) CERTIFICATION OF BUILDING PRODUCTS—AN ALTERNATIVE TO EPD AND HPD

As mentioned in Section 10.6, the evaluation of the suitability of a building product, based on the EPD data, is the task of the design team. Because of its extreme complexity, it is often difficult for the design team to analyze EPD data correctly to reach an appropriate conclusion, and the same applies to HPD data also.

The Cradle-to-Cradle (C2C) certification of products makes the above task easier. A C2C certification assesses the sustainability of a product based on the following five parameters:

i. Material health
ii. Material reutilization
iii. Renewable energy and carbon management
iv. Water stewardship
v. Social fairness

While the first four parameters deal with the impact of the product on the environment, the social fairness parameter considers the welfare of the stakeholders involved in making that product, to ensure that they are treated in a socially responsible way.

The C2C certification is an independent, third-party evaluation of a product provided through Cradle to Cradle Products Innovation Institute. A product may receive certification under five levels: (i) C2C Basic, (ii) C2C Bronze, (iii) C2C Silver, (iv) C2C Gold, and (v) C2C Platinum. LEED v4 recognizes C2C certification as a path to compliance in Materials and Resource Category as an alternative to EPD and HPD.

10.9 PRODUCT SUSTAINABILITY BASED ON A SINGLE ATTRIBUTE OR A LIMITED SET OF ATTRIBUTES

It may appear at first that sustainability metrics based on a single attribute or a limited number of environmental attributes have little use because they are not comprehensive. This is not true because for some products, only one or two sustainability attributes may be significant. For example, the most important environmental attribute of paints and adhesives is volatile organic compound (VOC) emissions. Emission ratings of these products, therefore, provide valuable information for facility managers, who may use these ratings along with several other factors (such as color, cost, and so on) in making their selection. Similarly, ratings of windows and glass curtain walls based on thermal performance (i.e., their impact on energy consumption) are a useful metrics because energy conservation is arguably the single most important sustainability attribute for windows and glass curtain walls.

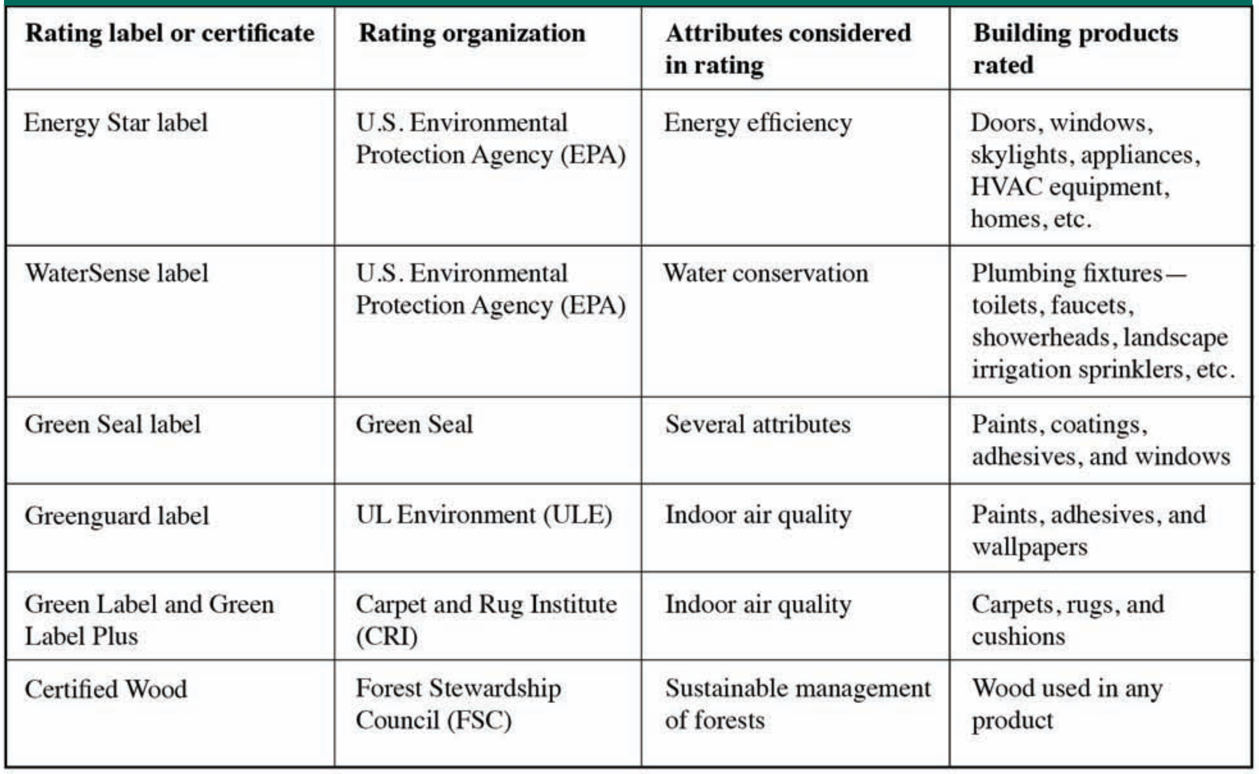
An additional advantage of single- or limited-attribute metrics is that they can be provided in the form of labels or marks (e.g., Energy Star label and Green Seal label), which are easy to comprehend and, therefore, better disposed to adoption. This is even simpler than C2C certification because of its several certification levels. Table 10.3 provides an overview of some of the commonly used metrics for assessing the greenness of building products based on single- or limited-environmental attributes.

ENERGY STAR LABEL FOR PRODUCTS

The Energy Star label was introduced by the U.S. Environmental Protection Agency (EPA) in 1992 to recognize energy-efficient computers. The program's success led to its extension to other product areas and its acceptance by several other countries. Thus, Energy Star is now an international energy-labeling system that rates and labels:

- appliances (refrigerators, air conditioners, washing machines, and so on)
- products (light bulbs and fixtures, office products, building products, and so on)
- homes
- commercial and industrial buildings

TABLE 10.3 LABELS AND CERTIFICATIONS OF SUSTAINABILITY OF BUILDING PRODUCTS BASED ON A SINGLE OR A LIMITED NUMBER OF ATTRIBUTES



Rating label or certificate	**Rating organization**	**Attributes considered in rating**	**Building products rated**
Energy Star label	U.S. Environmental Protection Agency (EPA)	Energy efficiency	Doors, windows, skylights, appliances, HVAC equipment, homes, etc.
WaterSense label	U.S. Environmental Protection Agency (EPA)	Water conservation	Plumbing fixtures—toilets, faucets, showerheads, landscape irrigation sprinklers, etc.
Green Seal label	Green Seal	Several attributes	Paints, coatings, adhesives, and windows
Greenguard label	UL Environment (ULE)	Indoor air quality	Paints, adhesives, and wallpapers
Green Label and Green Label Plus	Carpet and Rug Institute (CRI)	Indoor air quality	Carpets, rugs, and cushions
Certified Wood	Forest Stewardship Council (FSC)	Sustainable management of forests	Wood used in any product

Adapted from Ref. 10.6.

Among the building products, only those used in the building envelope are Energy Star rated, such as windows, skylights and exterior doors; insulation, radiant barriers, and air sealing products, and roofing products. Because different climate zones in the country have different energy-efficiency requirements, the Energy Star label on a door, window, or skylight shows the climate zone(s) for which the label is appropriate. An Energy Star–labeled door, window, or skylight certifies that its performance either equals or exceeds the requirements of the International Energy Conservation Code (see Chapter 5).

Energy Star Label for Buildings

A comprehensive Energy Star label is available for homes and commercial/industrial buildings. The label for new homes requires the energy analysis of the proposed home through the Home Energy Rating System (HERS)—a software package developed by the Residential Energy Services Network (RESNET). The analysis is performed by RESNET-approved raters based on the proposed home's construction drawings. The analysis yields a HERS index that determines if the proposed home meets the requirements of the Energy Star label and, if not, what improvements are needed.

The analysis is followed by inspections during construction and tests of air leakage after completion, called *blower tests*. Two blower tests are performed; one test determines the air leakage in the building envelope, and the other test determines the leakage in the HVAC duct system.

Homes built to reference design (RD) receive a HERS rating of 100. A HERS index greater than 100 indicates that the home is less energy efficient than the RD. Many older homes built prior to IECC's adoption belong to this category. A HERS index of less than 100 indicates that the proposed home is more energy efficient than the RD, Figure 10.14. RD is the design that satisfies the minimum prescriptive requirements of 2006 International Energy Conservation Code (IECC).

Each 1-point decrease in the HERS index implies 1% greater energy efficiency. Thus, a HERS index of 90 means that the proposed home is 10% more efficient than the RD home. A HERS index of zero means that it consumes no energy supplied by the external power grid. One of the options available to satisfy 2015 IECC for a home is that it should meet

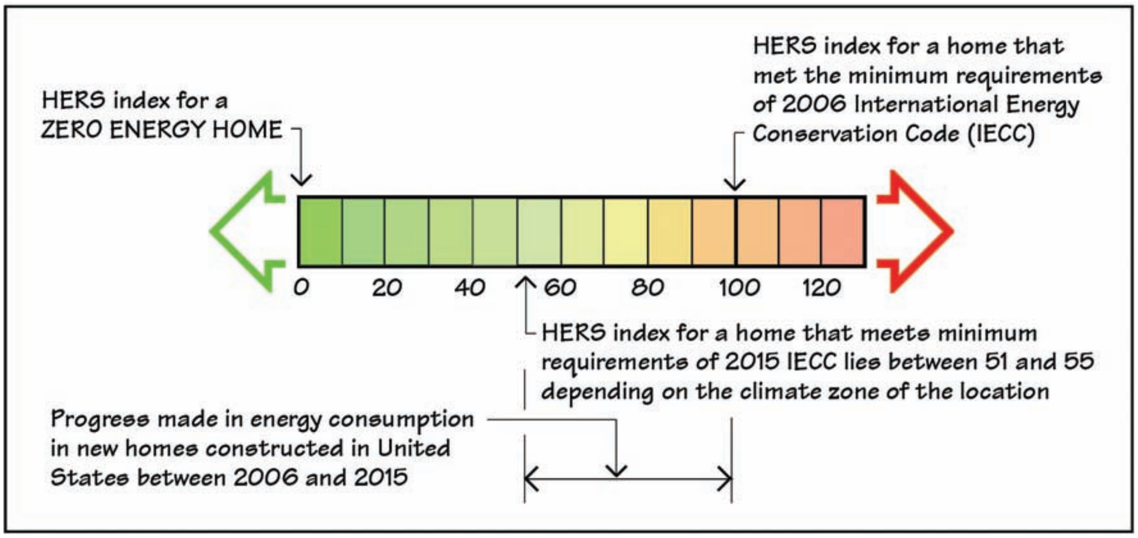

HERS index for a ZERO ENERGY HOME
HERS index for a home that met the minimum requirements of 2006 International Energy Conservation Code (IECC)
0
20
40
60
80
100
120
HERS index for a home that meets minimum requirements of 2015 IECC lies between 51 and 55 depending on the climate zone of the location
Progress made in energy consumption in new homes constructed in United States between 2006 and 2015

FIGURE 10.14 HERS index and 2015 International Energy Conservation Code.

HERS index requirement, which varies from 51 to 55, depending on the climate zone of the location [Ref. 10.7]. This requirement shows that a home built to the minimum requirements of 2015 IECC is 45% to 49% more energy efficient than the one designed to satisfy the minimum requirements of 2006 IECC. HERS index is a big marketing tool for speculative homebuilders.

WATERSENSE LABEL

Like the Energy Star label, WaterSense label has also been established in partnership with U.S. Environmental Protection Agency (EPA). The purpose of WaterSense label is to encourage the use of water-conserving devices such as toilets, urinals, showerheads, bathroom sink faucets, landscape irrigation sprinklers, and so on. It is estimated that WaterSense-labeled products save approximately 20% on water consumption. Reducing water consumption also reduces energy associated with water supply.

GREEN SEAL LABEL

The Green Seal organization has developed fairly stringent standards for measuring the greenness of several building products (such as paints, coatings, doors, and windows) based on a number of environmental attributes that are particularly relevant to the products. However, it is best known for its seals on residential and commercial cleaning products (hand cleaners, carpet cleaners, floor cleaners, and so on).

GREENGUARD CERTIFICATE

Greenguard certification focuses primarily on indoor air quality to certify products such as paints, adhesives, sealants, and interior furnishings, and is provided by the Greenguard Environmental Institute (GEI), which is particularly well known for certifying building construction that meets standards for mold prevention.

GREEN LABEL AND GREEN LABEL PLUS

Green Label is the mark assigned by the Carpet and Rug Institute (CRI) to carpets, rugs, and cushion materials that have low VOC emissions. Green Label Plus is a more stringent mark than Green Label.

CERTIFIED WOOD LABEL

The Certified Wood label is carried by wood products that have been produced by manufacturers according to the guidelines promulgated by the Forest Stewardship Council (FSC). The FSC guidelines prescribe responsible management practices for forest growth and harvesting that meet the social, economic, and environmental needs of the present and future generations. The FSC maintains a number of independent certifiers worldwide.

The two major FSC-accredited certifiers in the United States are SmartWood and Scientific Certification Systems. (See Chapters 13 and 14 for additional details.) Note that FSC's Certified Wood label refers only to the environmental management aspects of forests. It does not include other sustainability concerns, such as embodied energy or emissions of VOCs by engineered wood products.

10.10 UNIVERSAL BASELINE BUILDING SUSTAINABILITY—THE INTERNATIONAL GREEN CONSTRUCTION CODE

Since the launch of LEED v1 in 1998, there has been tremendous progress in the realization of the benefits of sustainable buildings in both public and private sectors, which led to an explosive growth in the popularity of USGBC and its LEED rating systems. However, the square footage that is covered by LEED rated buildings is fairly small as compared with the total square footage in all buildings constructed in the United States. Therefore, the overall, impact of greening U.S. building stock remains pretty insignificant, and the prospect of its betterment is not promising because of the voluntary nature of LEED rating system.

In realization of this fact, local jurisdiction across the United States have been adding mandatory building sustainability requirements for compliance through local ordinances for some time. The success of these initiatives led the International Code Council (ICC) in 2009 to begin work on a green construction code with the cooperation of AIA, ASTM International, USGBC, IES (Illuminating Engineering Society), and ASHRAE (American Society for Heating, Refrigerating, and Air-Conditioning Engineers). After necessary public reviews, the first edition of the model green code was published in 2012, called the 2012 *International Green Construction Code* (IGCC). This has been followed by its second edition in 2015—the 2015 IGCC.

Like all ICC family of codes, IGCC, when adopted by a jurisdiction, becomes mandatory for all buildings (with the exceptions mentioned later) within the jurisdiction. Because all codes are based on minimum requirements, IGCC provisions represent the minimum level of sustainability. In other words, the purpose of IGCC is to provide baseline sustainability in all buildings within the jurisdiction, thereby greening the jurisdiction's entire built environment to at least the baseline level.

As stated in Section 2.4, IGCC is an overlay code that is in harmony with other ICC codes, particularly the International Building Code (IBC). This implies that the jurisdiction's sustainability requirements will not conflict with its health and safety requirements. Additionally because the IGCC's enforcement is the responsibility of the jurisdiction, it is written in the format familiar to code officials, architects, and engineers.

LEED AND IGCC

Because both address building sustainability, there is a great deal of commonality between LEED and IGCC. In other words, IGCC deals with the same environmental impact categories as LEED, that is, sustainable sites, energy and atmosphere, materials and resources, indoor environment, and so on. Being a baseline code, IGCC is largely prescriptive, and virtually all its provisions are mandatory. On the other hand, LEED, being a rating system with four certification-level options, provides a great deal of flexibility in choosing the sustainability attributes that best fit the project. To an architect, engineer, or constructor, who is relatively new to sustainability, the prescriptive and baseline character of IGCC makes it easier to comply with. Those well versed with LEED, however, find LEED's flexibility an advantage.

Another major difference between LEED and IGCC is that there are different LEED rating systems for different types of buildings (schools, hospitals, data centers, etc). IGCC, on the other hand, is a single document which applies to all types of buildings. LEED also has a separate rating system for operations and maintenance, which applies to existing buildings. IGCC's chapter on existing buildings applies only where the existing building goes through major repairs, alterations, or change of occupancy.

Building sustainability in the code environment is new and evolving. Therefore, many jurisdictions have not yet allocated adequate resources to conduct an in-house review of construction documents for compliance with IGCC. A process that has gained sufficient acceptance in several jurisdictions is to use independent, third-party reviewers as an alternative. These reviewers are required to have appropriate credentials and go through jurisdiction-provided education and testing to demonstrate capability. Third-party reviews of construction documents for compliance with the codes has been used successfully by jurisdictions for quite some time.

BASELINE SUSTAINABILITY OF IGCC EQUIVALENT TO LEED CERTIFIED LEVEL

Because IGCC is mandatory for all buildings, an owner seeking LEED rating for the building will be subjected to a duplication of approvals, one from the USGBC and the other from the jurisdiction. To prevent this duplication, jurisdictions generally permit that if the building is seeking LEED rating to at least the Certified level, it need not be reviewed for compliance with the IGCC. In such cases, third-party reviewers, who are also knowledgeable about LEED rating systems, simplify the task for the jurisdiction as well as the owner.

IGCC AND ITS APPLICABILITY

IGCC applies primarily to nonresidential buildings. More specifically, it does not apply to:

a. One- and two-family dwellings (under the umbrella of the International Residential Code), and townhomes ≤3 stories in height.
b. Apartments and assisted living facilities ≤4 stories in height.

For residential buildings just stated, IGCC provides the option that they comply with National Green Building Standard (ANSI/ICC 700).

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

15. Which of the following building materials is most renewable?
a. Iron
b. Aluminum
c. Natural stone
d. Wood

16. Theoretically, all materials renew in nature within 50 to 100 years.
a. True
b. False

17. Per LEED v4, a material or product is considered locally produced if all its raw materials and manufacturing takes place within
a. 100 miles of the construction site.
b. 50 miles of the manufacturing facility.
c. 50 miles of the construction site.
d. 200 miles of the manufacturing facility.
e. 500 miles of the construction site.

18. Which of the two products, Product A or Product B, is considered by LEED v4 to contain larger amount of recycled content? Product A has 15% pre-consumer recycled content and 35% post-consumer recycled content. Product B has 35% pre-consumer recycled content and 15% post-consumer recycled content.
a. Product A
b. Product B

19. Per LEED v4, what is the total percentage of recycled content in a product which has 20 lb of pre-consumer recycled content and 25 lb of post-consumer recycled content? The total weight of the product is 100 lb.
a. 32.5%
b. 45%
c. 37.5%
d. 35%
e. None of the above

20. The term "EPD" is an acronym for
a. environmental purity data.
b. environmental parameter declarations.
c. environmental product declarations.
d. environmental performance data.
e. none of the above.

21. The number of environmental parameters considered in determining the EPD of a product are
a. six.
b. five.
c. four.
d. three.
e. seven.

22. The EPD of a product is a single-number index.
a. True
b. False

23. The EPD of a product is classified under two types, which are
a. 50-year EPD and 100-year EPD.
b. 60-year EPD and 100-year EPD.
c. 100-year EPD and life-cycle EPD.
d. cradle-to-gate EPD and cradle-to-grave EPD.
e. cradle-to-grave EPD and cradle-to-cradle EPD.

24. The environmental parameters used in determining the HPD of a product are
a. the same as those used in determining the life-cycle assessment of a building.
b. the same as those used in determining the EPD of a building.
c. the same as those used in determining the EPD of a product.
d. not required.

25. The C2C certification of a product is a multi-attribute certification.
a. True
b. False

26. The C2C certification of a product is available at
a. a single level.
b. two levels.
c. three levels.
d. four levels.
e. five levels.

27. A home with a HERS index of 50 is more energy efficient than one with a HERS index of 60.
a. True
b. False

28. The Certified Wood label considers all aspects of sustainability of wood.
a. True
b. False

29. The sustainability rating of a building based on the International Green Construction Code may be
a. Certified or Silver.
b. Silver or Gold.
c. Gold or Platinum.
d. Certified, Silver, Gold, or Platinum.
e. none of the above.

REVIEW QUESTIONS

1. For LEED v4 (BD+C), list the environmental impact categories used in determining the sustainability rating of buildings.
2. Explain the purpose of the following items in LEED v4.
    a. Integrative Process (IP)
    b. Regional Priorities (RP)
3. List various certification levels in LEED v4 (BD+C) and the differences between them.
4. Describe the role of commissioning in LEED BD+C rating system.
5. List various attributes that determine the sustainability of a building product and briefly describe their roles.
6. List the environmental parameters used in determining the EPD of a product.
7. List various types of EPD, per the International Organization for Standardization (ISO), and the differences between them.
8. Describe the difference between EPD and HPD.
9. Explain what C2C certification is, its purpose, and the levels of certification.
10. Using a sketch and notes, explain the HERS index and its relationship with IECC.

CHAPTER 11

Soils and Excavations

CHAPTER OUTLINE

11.1 CLASSIFICATION OF SOILS
11.2 GEOTECHNICAL INVESTIGATIONS—SOIL SAMPLING AND TESTING
11.3 SOIL TYPE AND EARTHQUAKES
11.4 BEARING CAPACITY OF SOIL
11.5 EARTHWORK FOR EXCAVATIONS AND GRADING
11.6 SUPPORTS FOR OPEN EXCAVATIONS
11.7 KEEPING EXCAVATIONS DRY
PRINCIPLES IN PRACTICE: UNIFIED SOIL CLASSIFICATION

As stated in Chapter 1, an important part of the pre-design phase of a building is site evaluation. This is a multifaceted evaluation. Some facets impact the construction materials and methods employed for the building significantly, while others play only a minor role. For example, the cost of land, the land use, and the site's accessibility to infrastructural services, though important, have a marginal impact on the construction aspects of the building. By contrast, several other site evaluation facets impact the construction aspects of the building substantially. These facets can be categorized as:

- Surface investigation of the site
- Subsurface (i.e., below-surface) investigation of the site

Surface investigation involves making a preliminary judgment about the site's suitability for the proposed building. The first part of surface investigation is a visual assessment of the site's topography, vegetation, storm water drainage pattern, foundation systems used in nearby buildings and their performance, and so on. If visual assessment concludes that the site is potentially suitable for the proposed building, the second part of the surface investigation—an engineering land survey of the site—is undertaken.

The land survey provides physical measurements of the site's boundaries, topography, drainage patterns, encroachments, easements, ownership, legal history, and so on, and is a critical component of the surface investigation. If the land survey analysis is favorable for the project, the next step is subsurface investigation of the site.

Subsurface investigation deals with conditions below the ground surface to determine the requirements for the foundations and excavations. Subsurface conditions have a significant influence on the building design, construction materials, structural system, construction cost, and schedule. For example, it is more expensive and time consuming to excavate in a rocky stratum or a stratum with a high water table. This chapter deals with aspects of subsurface investigation that impact foundation design and construction.

SOIL—A STRUCTURAL MATERIAL

The structural integrity of the building foundation is largely a function of the earth material (i.e., the soil) on which it rests. Because of its geological history, soil is a fairly complex material. Its complexity is embedded in its chemical composition, physical characteristics, variations in the depth below ground, and variations from location to location. The structural aspects of soils, as distinct from the soil's botanical characteristics (of interest to farmers), constitute a branch of study known as *soil mechanics*, or, more recently, as *geotechnical engineering* or *geostructural engineering*.

This chapter provides a brief and simplified discussion of soils' geotechnical characteristics that are essential for an architect or a constructor to know in order to make preliminary assessments and to communicate with geotechnical and structural consultants. It begins with a discussion of soil classification, leading to the methods used for field and laboratory investigations of soil properties. Because all foundation systems require some type of excavation, various methods of excavation and earthwork are presented. This is followed by a discussion of the support systems used to prevent the failure of deep excavation faces and trenches. This chapter concludes with a brief discussion of excavation dewatering.

11.1 CLASSIFICATION OF SOILS

If organic matter, which is present only in small quantities in most locations, is ignored, the earth's crust consists mainly of mineral (i.e., inorganic, noncombustible) matter. The earth's mineral matter is generally classified as *rocks* and *soils*.

In rocks, the mineral particles are firmly bonded together. Soil consists of either individual particles or a conglomerate of several easily separable particles that have resulted from the weathering of rocks (see the margin note). In most locations, the top layer of the ground consists of soil; rock generally occurs deep under the surface.

In most situations, the soil has adequate strength and other characteristics to support a building. When this is not the case, building foundations must bear on bedrock. (Rocks are classified as *igneous rocks, sedimentary rocks*, and *metamorphic rocks*; see Chapter 25.)

NOTE

Rock-Soil Cycle

In the early stages of the cooling of the earth from its molten state, the earth's crust consisted only of rocks. Abrasion caused by the movement of water and air on the earth's surface disintegrated rocks into smaller soil particles. Fatigue resulting from thermal expansion, contraction, freezing, and thawing of rocks enhanced their disintegration.

In addition to *mechanical weathering*, just described, rocks also went through *chemical weathering*, caused by their reaction with atmospheric oxygen, plant life, and various chemicals transported by water.

Both weathering processes continue to this day. As the disintegrated particles are carried by water and deposited in valleys, lakes, and deltas, they are eventually converted back to rock due to the pressure of overlying material. Thus, rock and soil formations are parts of a perpetual cycle referred to as the *geological cycle*.

Bedrock

Bedrock is continuous layer of native rock that has not weathered to soil. The depth of bedrock below the earth's surface may vary from a couple of feet to 100 ft or more.

GRAVELS, SANDS, SILTS, AND CLAYS

There are a number of characteristics that must be considered in determining the ability of a soil to support building loads. One important characteristic is soil classification based on the size of soil particles. The size of soil particles is measured by passing a dried soil sample through a series of sieves, each with a standardized opening size (see Figure 11.4). Soil particles that are retained in a No. 200 sieve are called *coarse-grained soils* (>0.075 mm), and soils that pass through this sieve are considered to be *fine-grained soils*.

As shown in Figure 11.1, coarse-grained soils are further divided into *gravels* or *sands*. Gravels have particles that are retained on a No. 4 sieve but are smaller than 3 in. Particles larger than 3 in. are called *cobbles* or *boulders*. Sand particles pass through a No. 4 sieve but are retained on a No. 200 sieve.

Fine-grained soils are divided into *silts* and *clays*. Particles smaller than 0.075 mm but larger than 0.002 mm are classified as silt. Particles smaller than 0.002 mm are classified as clay.

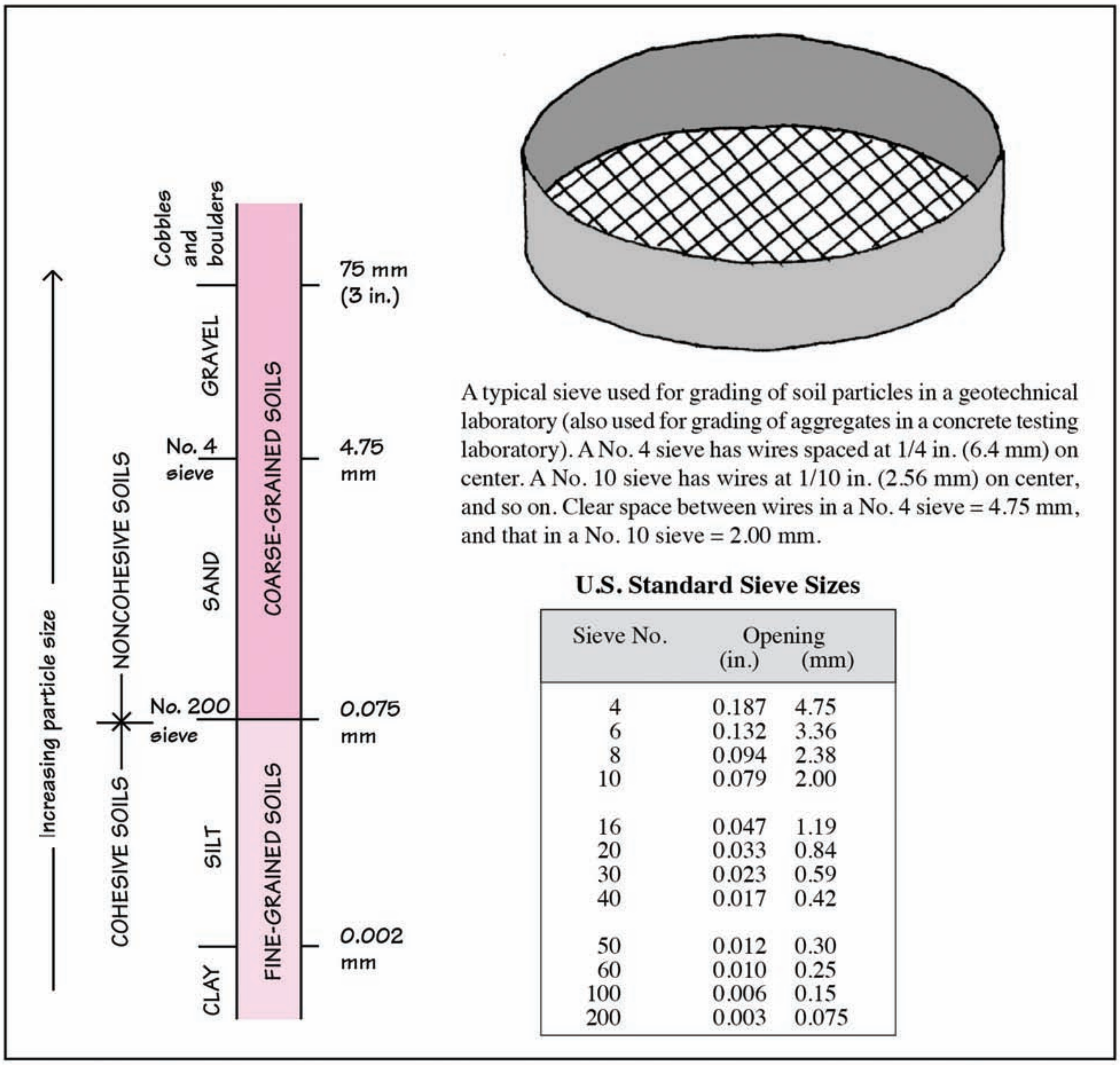
UNIQUENESS OF CLAY (SWELLING AND SHRINKING)—THE EXPANSIVE SOILS

Apart from the particle size, a major factor that distinguishes clay from other soil constituents is the particle shape. Gravel and sand particles are approximately equidimensional; that is, they are approximately spherical or ellipsoidal in shape. This is because gravels and sands are the result of mechanical weathering.

Clay particles, on the other hand, are the result of chemical weathering. They are, therefore, not equidimensional but have flat, platelike shapes. Because of their flat particle shape, the surface-area-to-volume ratio of clays is several hundred or thousand times greater than the corresponding ratio for gravels and sands. The characteristics of silt particles lie between those of clay and sand.

The behavior of clayey soils is greatly influenced by the electrostatic forces that develop between platelike surfaces. In the presence of water, these forces are repulsive, which increases the space between plates. Therefore, in the presence of water, clayey soils swell, and as water decreases (i.e., when they dry), they shrink.

Soils that are predominantly clayey are unstable because they expand and contract, depending on the amount of water present in them, and are referred to as *expansive soils*. If foundations supported on expansive soils are not designed to account for the soil's instability,



A typical sieve used for grading of soil particles in a geotechnical laboratory (also used for grading of aggregates in a concrete testing laboratory). A No. 4 sieve has wires spaced at 1/4 in. (6.4 mm) on center. A No. 10 sieve has wires at 1/10 in. (2.56 mm) on center, and so on. Clear space between wires in a No. 4 sieve = 4.75 mm, and that in a No. 10 sieve = 2.00 mm.

U.S. Standard Sieve Sizes

Sieve No.	Opening (in.)	Opening (mm)
4	0.187	4.75
6	0.132	3.36
8	0.094	2.38
10	0.079	2.00
16	0.047	1.19
20	0.033	0.84
30	0.023	0.59
40	0.017	0.42
50	0.012	0.30
60	0.010	0.25
100	0.006	0.15
200	0.003	0.075

FIGURE 11.1 The distinction between coarse-grained and fine-grained soils and between gravels, sands, silts, and clays. The term cobbles is used for pieces of naturally rounded rocks between 3 and 12 in. The term boulders describes similar material greater than 12 in. For U.S. standard sieve sizes, see American Society for Testing and Materials (ASTM), "Standard Specifications for Wire Cloth and Sieves for Testing Purposes", ASTM E11-04.

significant structural damage may occur, particularly to lightweight buildings, such as wood light-frame buildings. (See the section entitled "Expansive Soils" in Principles in Practice at the end of this chapter.)

COHESIVE AND NONCOHESIVE SOILS

One factor that distinguishes fine-grained from coarse-grained soils is the property of cohesion. Fine-grained soil particles adhere to each other in the presence of water and are, therefore, called *cohesive soils*. Coarse-grained soils are typically single-grained, lacking cohesiveness, and are referred to as *noncohesive soils*.

Clayey soils are more cohesive than silts. It is due to its cohesiveness that a potter can mold objects from wet clay, and excavated (cut) faces in a clayey soil can remain vertical without collapsing for a greater depth than other soil types. Even shallow excavations in noncohesive soils must be sloped for stability or shored by a support system.

11.2 GEOTECHNICAL INVESTIGATIONS—SOIL SAMPLING AND TESTING

Field exploration of below-ground soil conditions is an important first step before designing a building's foundations. The objectives of this exploration and sampling are to determine the:

- *Engineering properties of the soil* at various depths, such as the soil's strength (shear strength, unconfined compressive strength, triaxial compressive strength, and so on).
- These properties help determine the soil's bearing capacity.

NOTE

Organic Soils

When a soil consists largely of organic matter such as fully or partially decayed plant matter (peat), it is called *organic soil*. Organic soils are highly compressible and unsuitable for building foundations. They are typically dark in color and have a characteristic odor of decay. Additionally, they may have a fibrous texture due to bark, leaves, grass, branches, or other fibrous vegetable matter.

Organic soils form the top layer of soil and are typically removed before construction begins. If the soil characteristics are desirable, the soils are often stockpiled and redistributed after construction is complete.

- *Particle-size distribution of the soil* to assess the stability of cut faces, required excavation support, and the soil's drainage characteristics.
- *Plasticity index of the soil* to assess if the soil is unstable (shrinks and swells with changes in its moisture content); see Principles in Practice at the end of the chapter.
- *Nature of the excavation* that will suit the soil. (For instance, excavation in rock is more complicated and expensive than excavation in an ordinary soil.)
- *Depth of the water table* to plan for dewatering of excavations (if required) and its effect on existing construction.
- *Compressibility of the soil* to assess potential foundation settlement.

Two methods are generally used for field exploration: (a) the test pit method and (b) the test boring method.

TEST PIT METHOD

The test pit method consists of digging pits or trenches that are large enough for visual inspection of the soil and for procuring samples for laboratory testing by getting inside the pit or trench. It is considered to be the more reliable method because it allows direct inspection and assessment of several properties of the undisturbed soil through field tests with simple instruments.

There are several limitations to the test pit method. It is more expensive, and the cost increases substantially as the depth of the pit increases. Also, if the water table is high, the depth of inspection is limited.

TEST BORING METHOD

The test boring method, which is more commonly used, involves obtaining soil samples by boring into the ground using a truck-mounted, power-driven hollow stem fitted at the end with either a cutting bit or a fluted drilling auger. A typical drilling operation is shown in Figure 11.2.

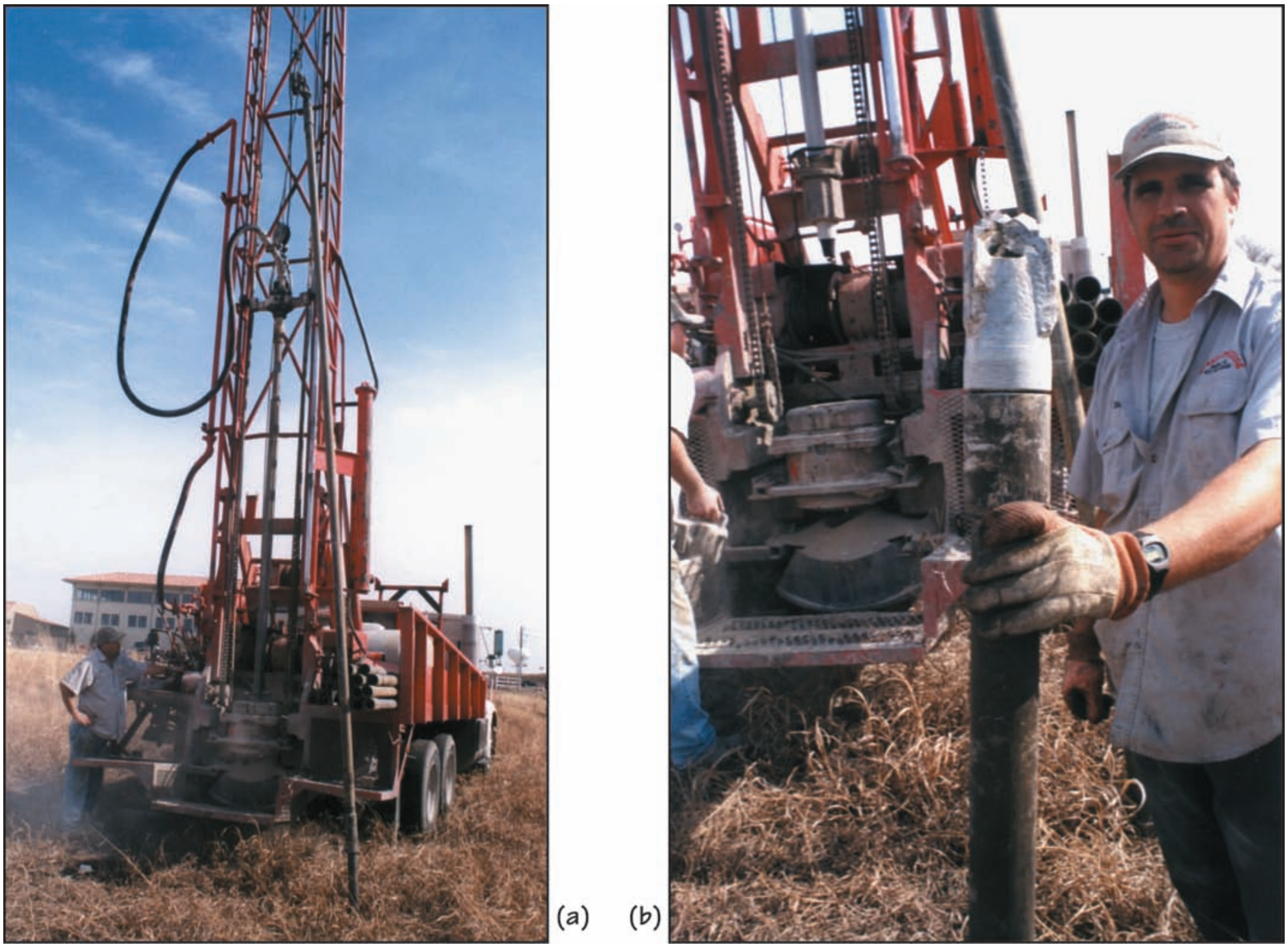


FIGURE 11.2 **(a)** A truck-mounted drilling machine bores a hole in the ground with a cutting tip at the end of a hollow pipe stem. During the drilling operation, compressed air is pushed through the hollow stem to suck the drilled soil out to keep the boring clean. After drilling to the required depth, the drilling bit is removed and a sampling tube is attached to the pipe stem to bring out a soil specimen. The process is repeated for various depths below ground. **(b)** A hollow pipe stem with a typical cutting bit.

When the boring reaches the depth at which a sample is required, the cutting bit is withdrawn and a standard steel sampling tube (called a *Shelby tube*) is pushed into the soil through its full height and the core sample is removed. (A tube that opens up into two semicircular halves, called a *split-spoon*, is also used instead of the Shelby tube. From a rocky soil, core samples are cut out.)

Soil specimens obtained from sampling tubes are wrapped in plastic, labeled with the required information, and transported to the testing laboratory, Figure 11.3. Several test borings are generally required across a large site, and the data obtained from various borings are coordinated. The test boring method also allows determination of the soil's density and strength by impacting the bottom of the boring with a standard amount of impact energy. The test, called the *standard penetration test*, is performed at several elevations in a boring.

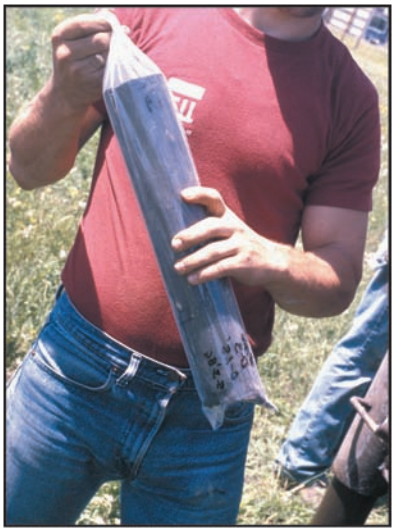


FIGURE 11.3 Soil samples obtained from borings through the use of a sampling tube are wrapped in plastic, labeled with the date of sampling, location of boring at the site, depth, and so on, and sent to a geotechnical laboratory.

LABORATORY TESTING OF SOIL SAMPLES

Soil samples obtained from pits or borings are subjected to a number of laboratory tests. The sieve analysis determines the particle-size distribution of the soil. This is used to classify the soil (see Principles in Practice at the end of this chapter). It also provides important information about several engineering properties of the soil. Sieve analysis is performed on an oven-dried part of the specimen by placing the sample on the uppermost sieve of a sieve stack, consisting of sieves of different sizes, Figure 11.4.

As shown in Figure 11.4, the bottom of the sieve stack is a No. 200 sieve. This sieve separates silts and clays from sand. In other words, sieve analysis is not performed to separate silts from clays because their particle size is too small to be separated by sieving. Instead, the soil sample retained on the No. 200 sieve is soaked in water, and the solution is agitated and then allowed to sediment (i.e., settle down). Because the heavier particles settle first, the rate of sedimentation provides information about the percentages of silts and clays.

Other tests include determining the soil's moisture content, dry density, liquid limit, plastic limit, compressive strength (unconfined, i.e., axial compressive strength, and confined, i.e., triaxial compressive strength), shear strength, and so on.

The data obtained during boring—from visual inspection of the soil, a standard penetration test, water table elevation, and so on—are immediately recorded on the testing laboratory's standard data sheet, referred to as the *boring field log*. After subsequent laboratory testing of samples, a final *boring log* is prepared. Each boring, therefore, results in its own boring log. One such log is shown in Figure 11.5.

11.3 SOIL TYPE AND EARTHQUAKES

In seismically active areas, different types of soils react differently to earthquake vibrations. Assume two types of subsurface conditions—one consisting of highly dense soil (e.g., bedrock as an extreme case) and the other consisting of loosely consolidated soil (soft soil),

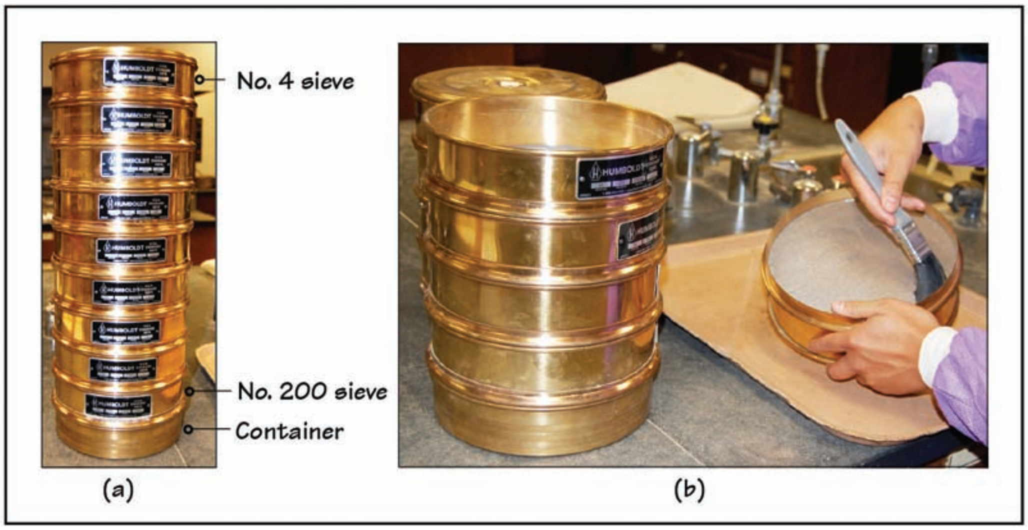


FIGURE 11.4 **(a)** A typical stack of sieves used to determine the grain-size distribution of oven-dried soil specimens. The top sieve is a No. 4 sieve and the bottom of the stack is not a sieve but a container. The sieve immediately above the container is generally a No. 200 sieve. The sieve stack is shaken per the standard procedure, either manually or by placing it on a motorized shaker. The amount of soil retained on each sieve is weighed. The amount obtained from the bottom container is the amount that passes through a No. 200 sieve. A graph showing the percentages of soil passing through various sieves is plotted. **(b)** After the sieve analysis is performed for a specimen, the sieves are cleaned and restacked for analyzing the next specimen.

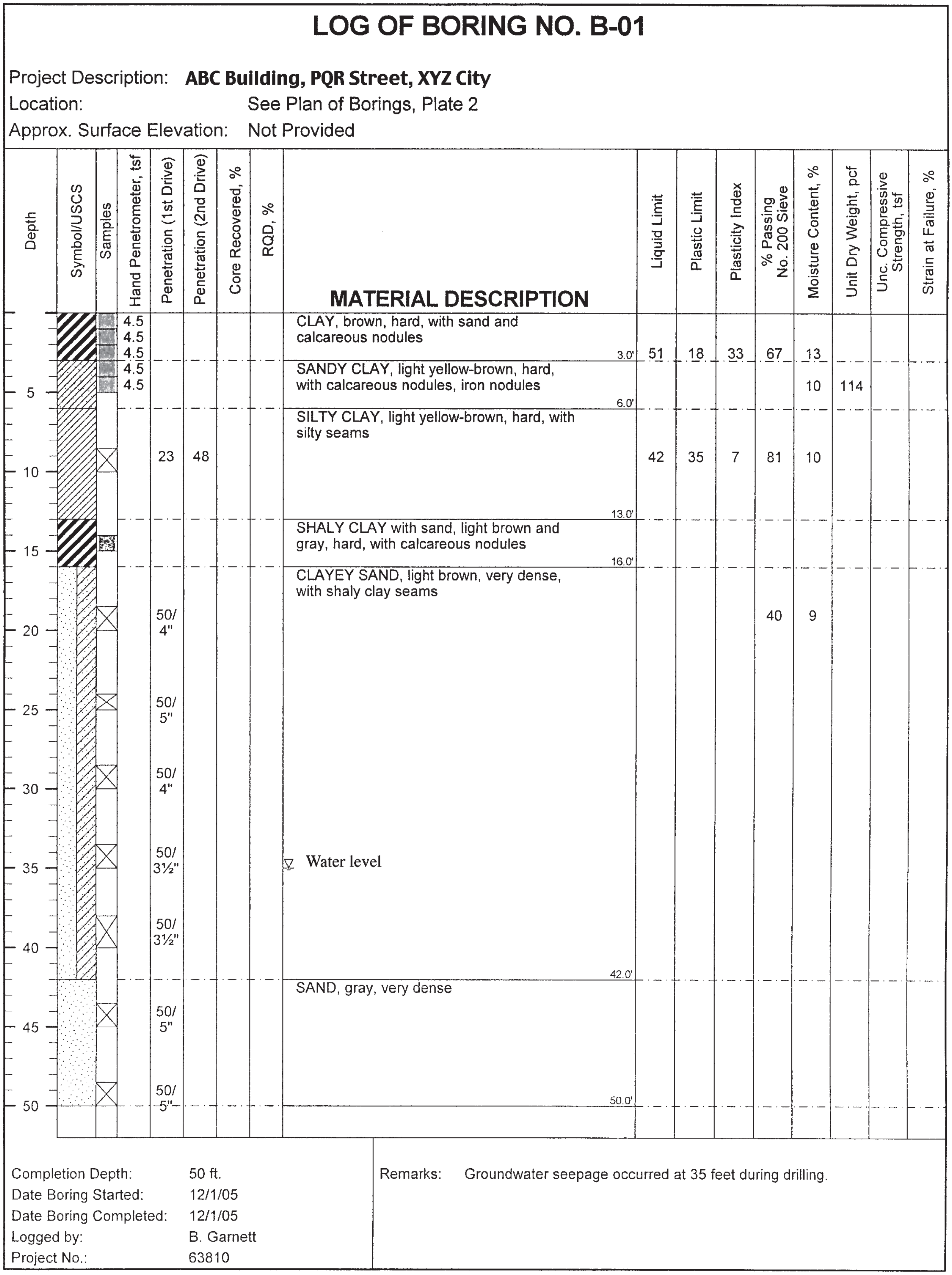
NOTE

Standard Penetration Test

The standard penetration test consists of striking the sampling tube with a hammer that delivers a standard amount of energy with each blow (a 140-lb weight falling over the tube through a height of 30 in.). The number of blows required to drive the tube through a depth of 6 in. is recorded.

The total number of blows for the second and third 6 in. of penetration (i.e., a total 12 in. of penetration) is called the *N-value* (or the *blow count* or the *standard penetration resistance*). The first 6 in. of penetration is ignored because it occurs in the disturbed part of the soil. A maximum of 50 blows are used, and if the tube penetrates less than 6 in. in 50 blows, the corresponding penetration distance is recorded. The test is generally performed every 5 ft of depth into the soil; see Figure 11.5.

The N-value is used as a rough index of the soil's bearing capacity, particularly for sandy soils. For a precise determination of the bearing capacity, other soil properties must be used along with the N-value.



LOG OF BORING NO. B-01

Project Description: **ABC Building, PQR Street, XYZ City**
Location: See Plan of Borings, Plate 2
Approx. Surface Elevation: Not Provided

Depth	Symbol/USCS	Samples	Hand Penetrometer, tsf	Penetration (1st Drive)	Penetration (2nd Drive)	Core Recovered, %	RQD, %	MATERIAL DESCRIPTION	Liquid Limit	Plastic Limit	Plasticity Index	% Passing No. 200 Sieve	Moisture Content, %	Unit Dry Weight, pcf	Unc. Compressive Strength, tsf	Strain at Failure, %
			4.5 4.5 4.5					CLAY, brown, hard, with sand and calcareous nodules 3.0'	51	18	33	67	13			
5			4.5 4.5					SANDY CLAY, light yellow-brown, hard, with calcareous nodules, iron nodules 6.0'					10	114		
10				23	48			SILTY CLAY, light yellow-brown, hard, with silty seams 13.0'	42	35	7	81	10			
15								SHALY CLAY with sand, light brown and gray, hard, with calcareous nodules 16.0'								
20				50/ 4"				CLAYEY SAND, light brown, very dense, with shaly clay seams				40	9			
25				50/ 5"												
30				50/ 4"												
35				50/ 3½"				∇ Water level								
40				50/ 3½"				42.0'								
45				50/ 5"				SAND, gray, very dense								
50				50/ 5"				50.0'								

Completion Depth: 50 ft.
Date Boring Started: 12/1/05
Date Boring Completed: 12/1/05
Logged by: B. Garnett
Project No.: 63810

Remarks: Groundwater seepage occurred at 35 feet during drilling.

FIGURE 11.5 A typical boring log. (Courtesy of Kleinfelder, Fort Worth, Texas) (See Principles in Practice at the end of this chapter for an explanation of some of the terms used in this log.)

Figure 11.6. Assume further that both of these subsurface conditions are subjected to the same earthquake motion. It is easy to see that the dense soil will vibrate less because of its high stiffness than the soft soil. In fact, the soft soil will amplify the vibrations because of its limpness. Consequently, a structure built on a highly dense soil (such as rock) will experience smaller deformations (hence will be subjected to a smaller earthquake load) than the same structure built on a soft soil.

This difference (between the vibrations of dense and soft soils) may be understood by imagining two identical bowls—one containing frozen water (representing the highly dense subsurface condition) and the other containing jello (representing soft soil). If both bowls are struck from the side with the same amount of force using a mallet, the frozen water in the bowl will vibrate the same way as the bowl, that is, very little. The vibrations of jello in the bowl, however, will be more vigorous.

This example represents two extreme soil conditions. Actual soil conditions range anywhere between these two extremes. Seismic load standards and building codes classify soils into six different types, depending on the stiffness of the soil. They are referred to as Site Classes A, B, C, D, E, and F. Site Class A represents hard rock; Class B represents rock; Class C is soft rock or dense soil; Class D is stiff soil; and Class E is soft soil. Class F represents highly sensitive soils that may experience consolidation or liquefaction as a result of ground motion. Geotechnical studies of the soil are required to determine the site class. Information about site class is one of the requirements in determining the earthquake loads on a building.

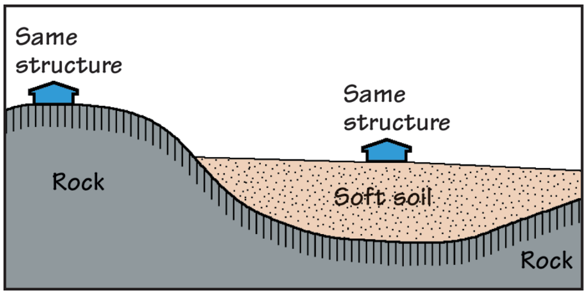


FIGURE 11.6 Soft soils amplify earthquake motion. Therefore, a structure located on a soft soil is subjected to a larger earthquake load than the same structure situated on a stiff soil, such as rock.

SOIL LIQUEFACTION

Some soils will liquefy under seismic vibrations, losing all their strength. Soil liquefaction usually occurs in water-saturated, sandy soils in which the particles of sand are of relatively uniform size. In such soils, the amount of interparticle space is large; hence, these soils hold greater amounts of water. When such soils are shaken, they consolidate and the water rises to the surface, resulting in loss of foundation support to buildings constructed on them. The most notable example of soil liquefaction occurred in Niigata, Japan, during the 1964 earthquake. In this earthquake, several high-rise buildings simply tipped over while otherwise remaining intact.

NOTE

Soil Classification and Earthquakes

Class A Hard rock
Class B Rock
Class C Soft rock (dense soil)
Class D Stiff soil
Class E Soft soil
Class F Highly sensitive soil

11.4 BEARING CAPACITY OF SOIL

One of the most important properties of a soil derived from laboratory tests is the soil's *bearing capacity*. The bearing capacity of a soil is its strength to bear loads imposed on it by the structure (see also Section 4.8). It is expressed in pounds per square foot (psf) or kips per square foot (ksf). In other words, the bearing capacity of a soil determines the maximum load that can be placed on each square foot of the soil before it fails structurally or has an unacceptable amount of settlement.

Because there must be a factor of safety, we use the *allowable bearing capacity* value in the design of foundations. The allowable bearing capacity is smaller than the failure (ultimate) bearing capacity and includes the safety factor (generally 3.0). Note that the term *bearing pressure* is technically more precise than *bearing capacity*, but both terms are used interchangeably.

The greater the allowable bearing capacity of the soil, the smaller is the area (spread) required for the footing under the foundation element. For example, if the load on a column footing is 200 kips and the soil's allowable bearing capacity is 4 ksf, the area of column footing required is $200/4 = 50$ ft^2. If the allowable bearing capacity is 5 ksf, the footing area required is $200/5 = 40$ ft^2 (1 kip $=$ 1,000 lb).

As previously stated, the allowable bearing capacity of soil generally increases with increasing depth below ground because the deeper strata of native soil are generally more densely compacted and have a smaller amount of decomposed plant matter. Therefore, increasing the depth below ground for the base of the footing generally reduces the footing area but increases the depth of excavation, Figure 11.7. Thus, the bearing capacity of the soil is generally evaluated at various levels below ground to establish the most suitable level for the base of the footing—to balance the footing area with the amount of excavation needed.

DEPTH OF THE FROST LINE

A soil property that is even more critical than the soil's bearing capacity is its stability. As previously stated, an unstable soil (such as a predominantly clayey soil) is unfit for foundation

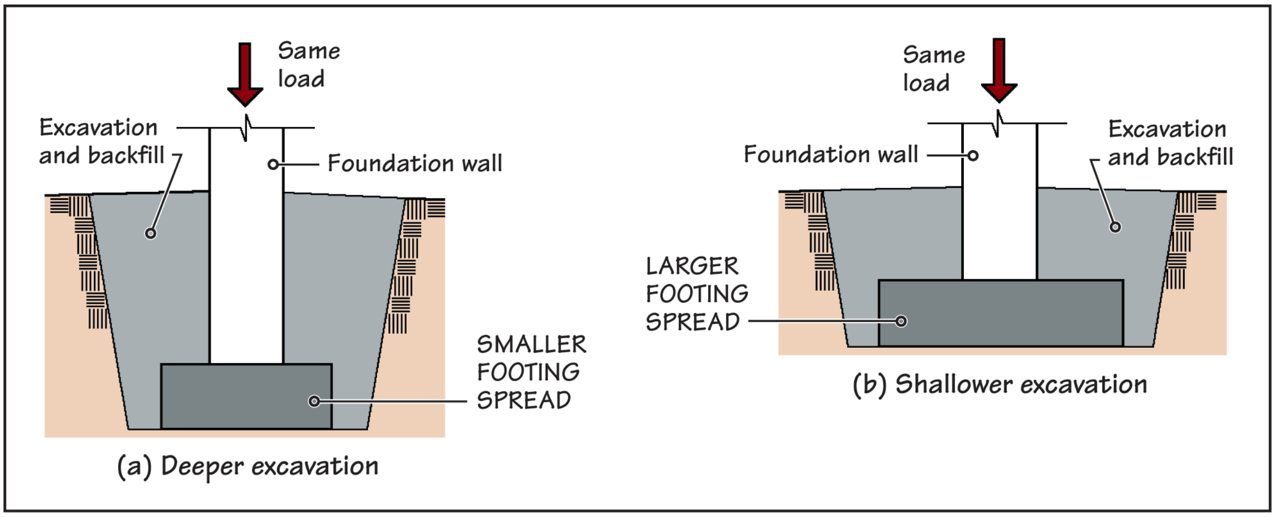


FIGURE 11.7 The bearing capacity of soil at a site generally increases with the depth below ground. Consequently, the footing area (spread) required is smaller if the base of the footing is located deeper in the ground. However, going deeper into the ground increases the excavation depth, somewhat negating the benefit of the smaller footing area. A balance between these two opposite effects is generally sought unless there are other considerations.

support. In such soils, the foundation elements must penetrate deep into the ground to a depth where the soil is stable and has sufficient bearing capacity.

Another factor (apart from the soil's clay content) that produces instability is the freezing of the ground, which is defined by the *frost depth*. The frost depth (also called the *freezing depth*) at a location is the maximum depth into the ground beyond which the water in the soil will not freeze. The frost depth is larger in colder climates. In the continental United States, the frost depth varies from approximately 6 in. in southern regions to approximately 90 in. in northern regions. The building departments of municipalities provide more accurate information.

The base of a footing must extend below the frost depth. If the base of the footing is above the frost depth, the freezing of water in soil will cause the soil under the footing to heave, damaging the footing. In Canada and the northern United States, the depth below ground for the base of footings for lightweight structures is generally controlled by the frost line, not by the allowable bearing capacity of the soil.

Frost depth is not an issue with bedrock because of the absence of water. For the same reason, it is not an issue with a soil that does not hold water, such as free-draining soils with gravel or coarse sand.

PRESUMPTIVE BEARING CAPACITY OF SOIL

The allowable bearing capacity of a soil should be obtained from geotechnical investigations of the site. However, its approximate value, based on the particle size of the soil at the location (without geotechnical investigation) is allowed to be used in situations where:

- the building is small;
- adequate information about the soil from adjoining areas is available;
- the site does not contain fill of an unknown origin; and
- the soil is known to be stable (nonexpansive).

Table 11.1 gives approximate (presumptive) allowable bearing capacity values, as stated in the International Building Code. The code values are highly conservative and, hence, their use generally results in overdesign of foundation systems. In larger structures, it is, therefore, more economical to seek formal subsurface soil investigation.

NOTE

Relationship Between Foundations and Footings

As previously stated, the load-bearing capacity of the earth's surface generally increases with depth below the ground. Therefore, unless the ground surface at a building site consists of stable, hard rock, the structural elements of a building (such as load-bearing walls and columns) must be taken below the ground—to a stratum where the soil is stable and has adequate strength to carry the superimposed loads. The part of the structural system below the ground floor of the building (below the basement floor if the building has a basement) that carries the load into the ground is called the *building foundation system* (see also the introduction to chapter 12).

The soil on which the load-bearing walls and columns rest is generally weaker than the materials used to construct the walls and columns. Therefore, the walls and columns generally need to be widened at their bases to ensure that the bearing pressure on the soil is less than its bearing capacity. These widened parts are called the *footings*. Note that footings are part of the foundation system. (A detailed discussion of foundation systems is presented in Chapter 12.)

TABLE 11.1 PRESUMPTIVE ALLOWABLE BEARING CAPACITY OF SOILS

Class of material	Allowable bearing capacity
Crystalline bedrock	12.0 ksf
Sedimentary and foliated rock	4.0 ksf
Soil types GW and GP	3.0 ksf
Soil types SW, SP, SM, SC, GM, and GC	2.0 ksf
Soil types CL, ML, MH, and CH	1.5 ksf

For symbols of soil types, refer to the Unified Soil Classification System in Principles and Practice at the end of this chapter.
Source: From International Code Council, International Building Code, 2009, Chapter 18. P. 392. Published by ASTM International.

Each question has only one correct answer. Select the choice that best answers the question.

1. Soil and rock consist essentially of the same matter.
   a. True **b.** False
2. In the commonly used soil classification system, *sand and silt* are classified as
   a. coarse-grained soils.
   b. fine-grained soils.
   c. organic soils.
   d. inorganic soils.
   e. none of the above.
3. The four commonly used classifications of soils arranged in order of decreasing particle size are
   a. gravel, sand, silt, and clay.
   b. gravel, silt, sand, and clay.
   c. gravel, silt, clay, and sand.
   d. gravel, sand, clay, and silt.
   e. none of the above.
4. Which of the following statements is correct?
   a. Gravel particles have a platelike shape.
   b. Sand particles have a platelike shape.
   c. Silt particles have a platelike shape.
   d. Clay particles have a platelike shape.
5. Cohesive soils are those in which the dry soil particles tend to separate from each other when mixed with a small amount of water.
   a. True **b.** False
6. To obtain soil-sampling tubes from below ground, which soil-testing method is commonly used?
   a. Test pit method
   b. Test boring method
   c. Test pressure method
   d. Any one of the above
   e. None of the above
7. During soil testing, soil samples are obtained from
   a. one central location on the site but from different depths below ground.
   b. several locations on the site but from the same depth below ground.
   c. several locations on the site and from several depths below ground.
   d. none of the above.
8. All testing of soil samples is generally done at the site
   a. because modern soil sampling equipment is fully equipped with soil testing facility.
   b. because the delay in bringing soil samples to the laboratory falsifies test results.
   c. because the vibration of soil samples caused by transportation falsifies test results.
   d. all of the above.
   e. none of the above.
9. In terms of soil behavior in earthquakes, building codes classify a construction site based on soil conditions. The primary property of soil that is used in this classification is
   a. the stiffness/density of soil.
   b. the size of soil particles.
   c. the swelling and shrinkage characteristics of soil.
   d. whether the soil is native to the site.
   e. none of the above.
10. The bearing capacity of a soil refers to
    a. the density of soil.
    b. the modulus of elasticity of soil.
    c. the compressive strength of soil.
    d. whether the soil is native to the site.
    e. none of the above.
11. The bearing capacity of a soil is generally expressed in terms of
    a. pounds or kips per square foot.
    b. pounds or kips per square inch.
    c. pounds or kips per cubic inch.
    d. pounds or kips per inch.
    e. pounds or kips.
12. If the bearing capacity of the soil is high, the footing area required is large.
    a. True **b.** False
13. The maximum presumptive bearing capacity value of bedrock provided by the International Building Code is
    a. 18.0 ksf.
    b. 16.5 ksf.
    c. 15.0 ksf.
    d. 12.0 ksf.
    e. none of the above.
14. The building codes do not mandate geotechnical investigations for all building construction sites.
    a. True **b.** False

11.5 EARTHWORK FOR EXCAVATIONS AND GRADING

Site preparation in advance of construction generally includes:

- Fencing the site from adjacent public or private property.
- Locating and marking existing underground utility lines so that they will not be damaged during construction.
- Demolishing unneeded existing structures and utility lines.
- Marking trees to be saved, and removing unneeded trees, shrubs, topsoil, and extraneous landfill, if present.

EXCAVATION

Excavation is the first step of construction. It refers to the process of removing soil or rock from its original location, typically in preparation for constructing foundations, basements, and underground utility lines and for grading of the ground surface. Excavated material required for backfill or grading fill is stockpiled on the site for subsequent use. Unneeded material is removed from the site for appropriate disposal. Excavations are generally classified as:

- Open excavations
- Trenches
- Pits

NOTE

Types of Fill—Backfill, Grading Fill, Select Fill, and Engineered Fill

Backfill refers to the material excavated from the site that is used to fill the excavated trenches or pits after constructing the foundations or basement. Unless the excavated material is unsuitable, backfill involves returning the excavated material to its original location.

Grading fill (also called *fill*) is a soil that is used for grading work—to bring the finished ground surface to the required contours and slope for drainage, landscaping, erosion control, aesthetics (land form), and so on, as per the site design. Generally, the material not used as backfill is used as grading fill unless it is unsuitable.

Select fill is a soil with required properties that is imported to a given site, placed, and compacted to produce the desired result. For example, a select fill may consist of a coarse-grained, stable soil to replace the existing expansive (clayey) soil at a site.

Engineered fill is a soil that is specially prepared, placed, compacted, and supervised per the geotechnical engineer's design and specifications. For example, it may be soil mixed with crushed angular aggregate of a required grading to give a controlled void space to increase storm water retention and reduce runoff.

Open excavations refer to large (and often deep) excavations, such as for a basement. *Trenches* generally refer to long, narrow excavations, such as for footings under a wall or utility pipes. *Pits* are excavations for the footing of an individual column, elevator shaft, and so on.

The depth of excavation depends on the type of soil and the type of foundation. For a slab-on-ground, the depth of excavation is small, whereas the depth of excavation for a basement is directly related to the number of basement floors. For trenches and pits, the excavation must reach soil with sufficient bearing capacity to support the load. If the soil with the required bearing capacity and stability is not present at a reasonable depth, deep foundation elements, which do not require conventional excavation (see Chapter 12), are used.

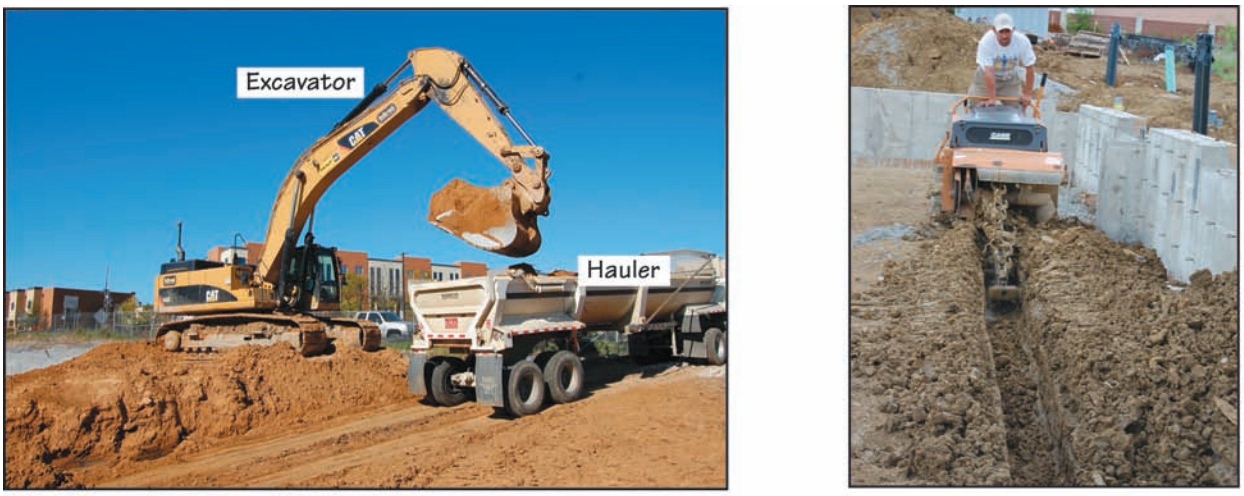
GRADING

Grading involves moving earth from one location of the site to another and changing the existing land surface to the desired finished surface configuration as per the site plan and drainage plan. On most sites, grading is separated into rough grading and finish grading. Rough grading is done along with excavations for foundations, basements, and utility trenches. Finish grading is generally done toward the end of the project as per the landscape design.

Both excavation and grading require various types of power equipment, such as excavators, compactors, and heavy earth-moving equipment (front-end loaders and backhoes), some of which are shown in Figure 11.8.

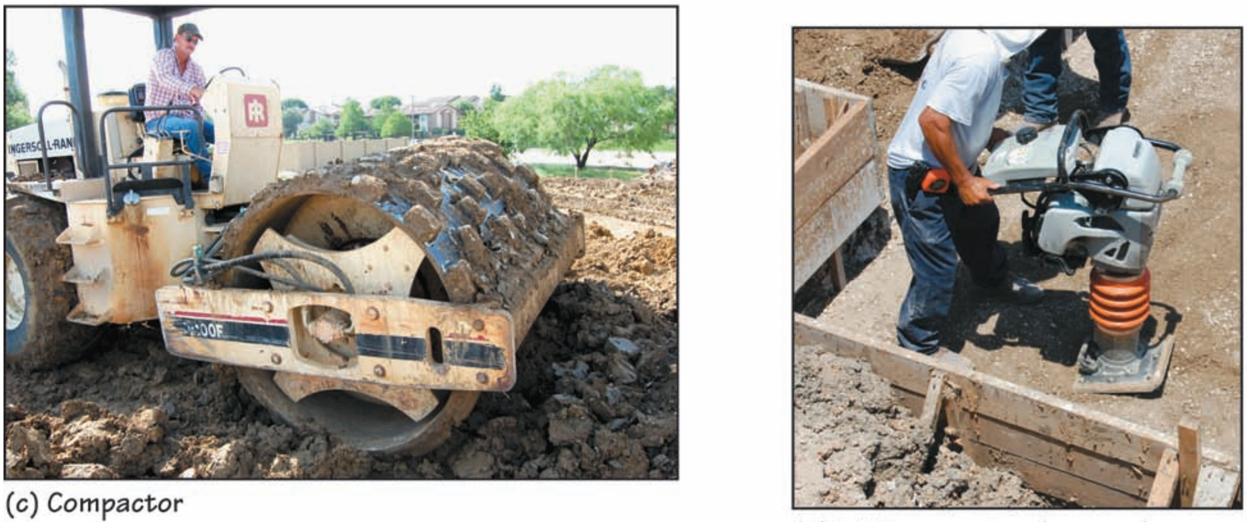
11.6 SUPPORTS FOR OPEN EXCAVATIONS

Excavations in the soil generally require some type of support to prevent cave-ins while the foundation system or basement walls are constructed. The simplest excavation support



(a) Excavator and hauler

(b) Trencher



(c) Compactor

(d) Mini compactor (rammer), generally used for compacting small areas

FIGURE 11.8 Some of the equipment used for earthwork (excavation, hauling, and compaction).

system consists of providing adequate slope in the excavated (cut) face so that it is able to support itself, Figure 11.9. This is feasible only if the site is large enough to accommodate sloped excavations. Because the amount of excavated material is large, sloped excavations also require a larger site area for stockpiling the material until it is used as grading fill or backfill.

The maximum natural slope at which a soil will support itself must be determined from soil investigations. Excavation in coarse-grained soils requires a shallower slope than excavation in fine-grained soils. A sloped excavation may either be uniformly sloped or stair-stepped, called a *benched excavation*, Figure 11.10. Benches increase slope stability. They are also easier to compact. Compacted benches further enhance slope stability.

Self-supporting sloped excavations cannot be provided where the site area is restricted or adjoining structures are present. In these cases, the excavation must consist of vertical cuts. In cohesive soils, shallow vertical cuts (generally 5 ft or less in depth) may be possible without any support system. Deeper vertical cuts must be provided with a support system. These support systems may be temporary (removed after the construction is complete) or permanent. Some of the commonly used methods of supporting deep vertical cuts in the soil are:

- Sheet piles
- Cantilevered soldier piles
- Anchored soldier piles
- Contiguous bored concrete piles
- Secant piles
- Soil nailing
- Bentonite slurry walls

EXCAVATION SUPPORT FOR DEEP VERTICAL CUTS—A TOP-DOWN CONSTRUCTION SYSTEM

All the support systems just listed involve the construction of an earth retention system. Because the excavated cuts are constructed in vertical segments, proceeding from the top and moving downward, the system of construction is referred to as *top-down construction*. In this system, the earth pressure is resisted by the excavation support system, and a separate basement wall is constructed (where needed) abutting the excavation support, Figure 11.11(a). Thus, the basement wall is not subjected to any earth pressure.

This is in contrast to the construction of a conventional basement wall, where the excavation for the entire height of the wall is made first (e.g., using the sloped excavation shown in Figure 11.9) and the basement wall is constructed subsequently. In this case the earth retention is provided by the basement wall, which is constructed from the bottom up, Figure 11.11(b). In top-down construction, the earth retention is provided by the excavation support system, and is the system of choice for deep excavations and tight sites.

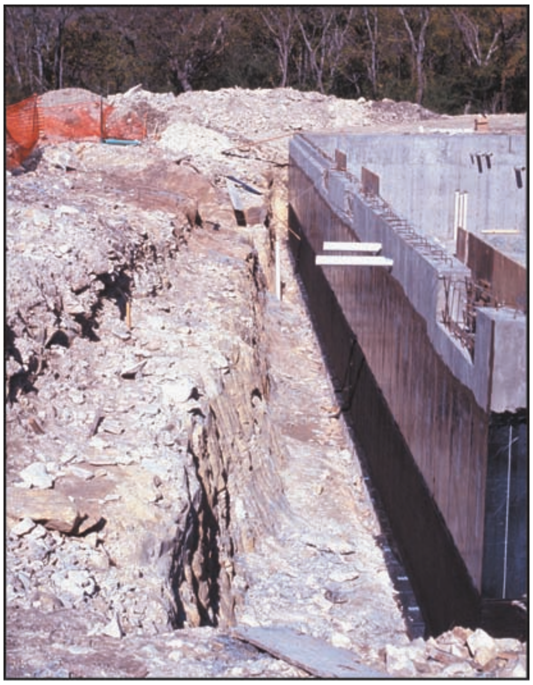
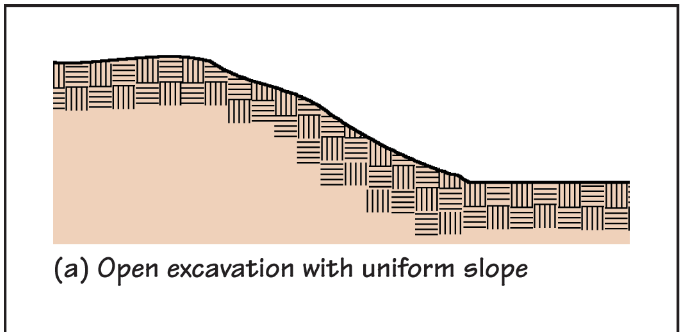
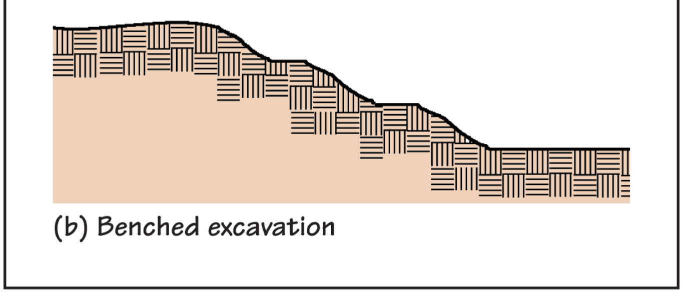


FIGURE 11.9 An example of a self-supporting open excavation for a basement.

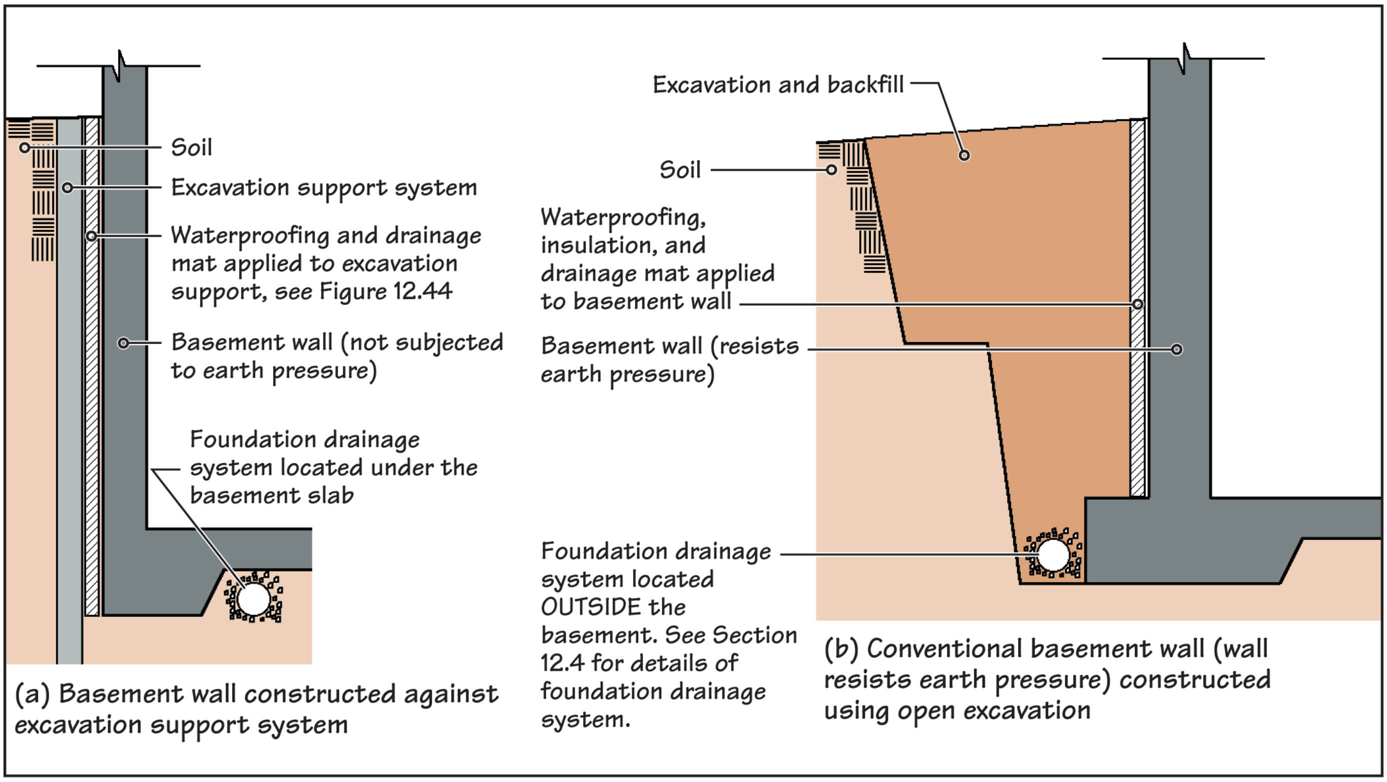


(a) Open excavation with uniform slope



(b) Benched excavation

FIGURE 11.10 Two alternative methods used for self-supporting open excavations.


Soil
Excavation support system
Waterproofing and drainage mat applied to excavation support, see Figure 12.44
Basement wall (not subjected to earth pressure)
Foundation drainage system located under the basement slab
Excavation and backfill
Soil
Waterproofing, insulation, and drainage mat applied to basement wall
Basement wall (resists earth pressure)
Foundation drainage system located OUTSIDE the basement. See Section 12.4 for details of foundation drainage system.

(a) Basement wall constructed against excavation support system

(b) Conventional basement wall (wall resists earth pressure) constructed using open excavation

FIGURE 11.11 Two alternative ways of constructing a basement: **(a)** basement wall not subjected to earth pressure (the earth pressure is resisted by an independent excavation support system), and **(b)** earth pressure resisted by the basement wall. Provisions for the drainage of subsoil water are essential in both cases. Several details (e.g., waterproofing of the basement slab) are not shown for clarity. Refer also to Figures 12.43 to 12.45.

In both cases, it is important to provide sufficient drainage to drain water from the soil behind the basement wall (in conventional construction) or behind the excavation support system, because wet soil exerts significantly greater pressure than dry soil.

EXCAVATION SUPPORT USING SHEET PILES

For depths of up to about 15 ft, vertical sheets of steel, referred to as *sheet piles*, can be driven into the ground before commencing excavations. Sheet piles consist of individual steel sections that interlock with each other on both sides. The interlocks form a continuous barrier to retain the earth. Structurally, sheet piles function as vertical cantilevers and, therefore, must be buried in the soil for sufficient depth below the bottom of the excavation. (Sheet piles are also used as permanent barriers against water, e.g., harbor walls, flood-protection walls, and so on.)

Sheet piles are available in many cross-sectional profiles. The most commonly used profile is a Z-section, Figure 11.12. The sections are driven into the ground one by one using either hydraulic hammers or vibrators, Figure 11.13.

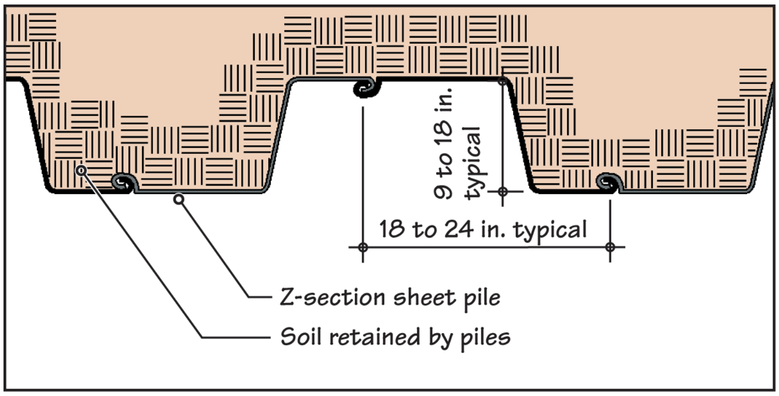

9 to 18 in. typical
18 to 24 in. typical
Z-section sheet pile
Soil retained by piles

FIGURE 11.12 Steel sheet piles with a Z-shaped profile. Adjacent sections interlock with each other. Several other sectional profiles are also available.

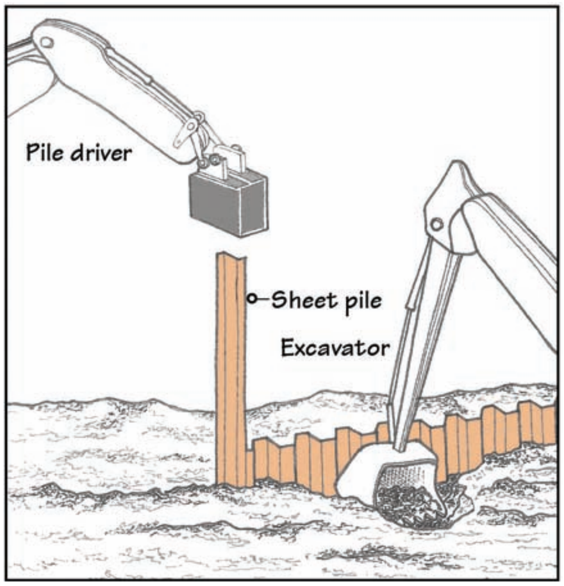

Pile driver
Sheet pile
Excavator

FIGURE 11.13 Sheet piles being driven into the ground. After the piles have been driven to the required depth below ground, excavation of the soil is undertaken.

EXPAND YOUR KNOWLEDGE

Top-Down Construction for an Entire Building

The top-down method of construction is applicable not only to excavation supports but also to the construction of an entire building. The method allows the construction of the basement and the above-ground structures simultaneously and is, therefore, also called the *up-and-down method* of construction. It reduces construction time, particularly for buildings with several basement floors, commonly used in downtown metropolitan areas.

In this method, perimeter basement walls are constructed first, using secant piles or concrete diaphragm walls (described in Section 11.6). Next, drilled piers are constructed up to the ground floor level at locations indicated for building columns in the plans (see Section 12.4 for the construction of drilled piers). The piers function as supports for the above-ground columns and as columns for the basement structure. The ground floor is now constructed, leaving some bays of the ground floor structure open to allow access for basement excavation.

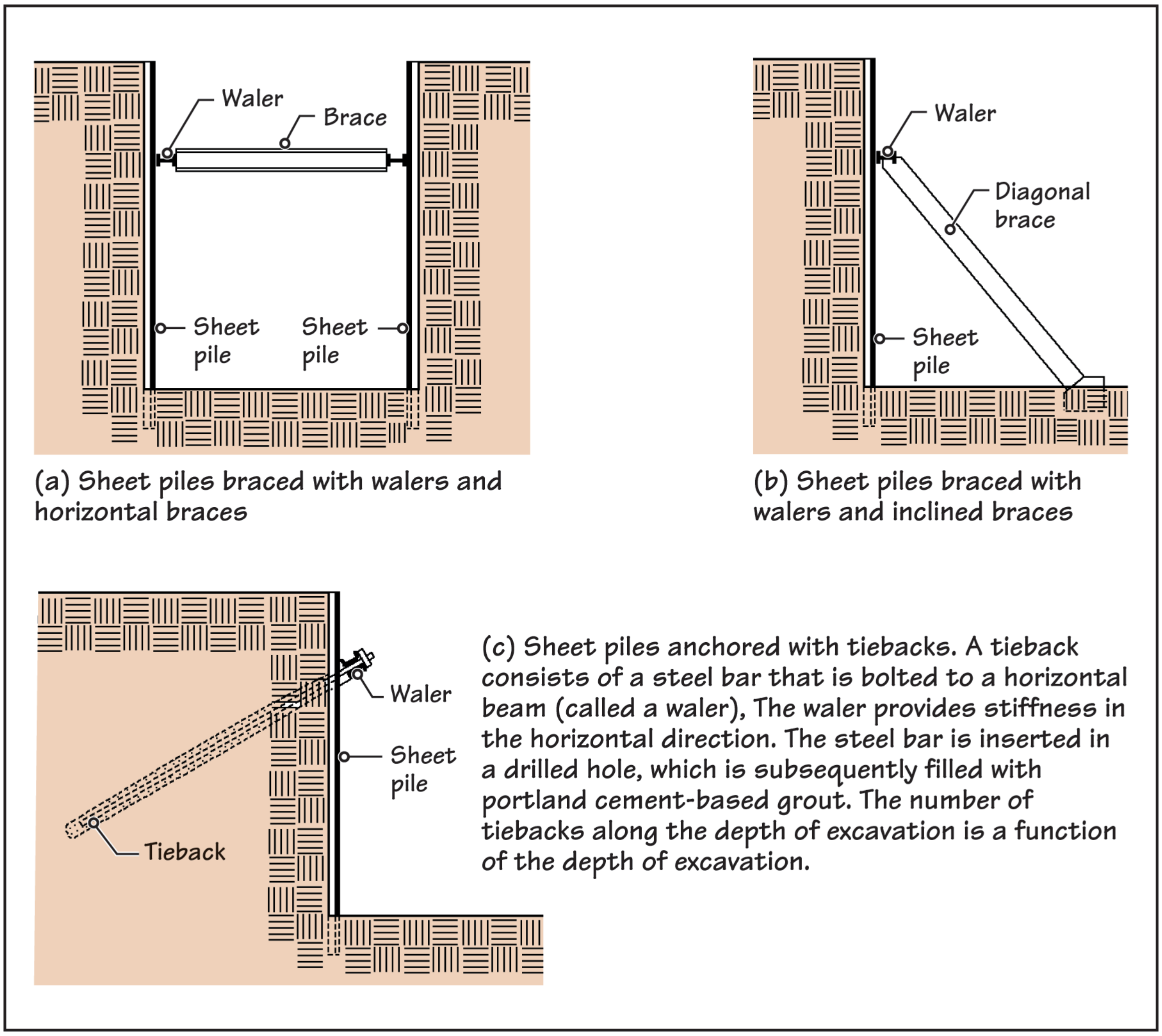
After the construction of the ground floor structure, columns and other structural elements of the building for the upper floor are constructed while the excavation for the first basement level continues simultaneously. The excavation for the basement exposes the piers and the diaphragm walls. As previously stated, the piers function as basement columns, and the diaphragm walls function as outer basement walls.

Because the vertical support elements for the first basement floor are already in place, this floor is now constructed, again leaving a few access openings for the excavation of the lower basement levels. Note that the floor of each basement acts as lateral support for the diaphragm walls. The process described continues for additional above-ground and below-ground levels.

For deeper excavations (generally greater than 15 ft), sheet piles are braced with horizontal or inclined braces or anchored with tiebacks, Figure 11.14. Sheet piles are removed after they are no longer required or can be left in place if needed.

EXCAVATION SUPPORT USING CANTILEVERED SOLDIER PILES

One of the disadvantages of sheet piles is the noise and vibration created in driving them, particularly in stiff soils where the vibratory method is ineffective and hydraulic hammers must be employed. An alternative to sheet pile excavation support is the soldier pile system. In this support system, H-shaped steel columns (called *soldier piles* or *H-piles*) are placed in



(a) Sheet piles braced with walers and horizontal braces

(b) Sheet piles braced with walers and inclined braces

(c) Sheet piles anchored with tiebacks. A tieback consists of a steel bar that is bolted to a horizontal beam (called a waler), The waler provides stiffness in the horizontal direction. The steel bar is inserted in a drilled hole, which is subsequently filled with portland cement-based grout. The number of tiebacks along the depth of excavation is a function of the depth of excavation.

FIGURE 11.14 **(a)** and **(b)** Two alternative ways of bracing sheet piles in deep excavations—horizontal and inclined braces. **(c)** Sheet piles with tiebacks.

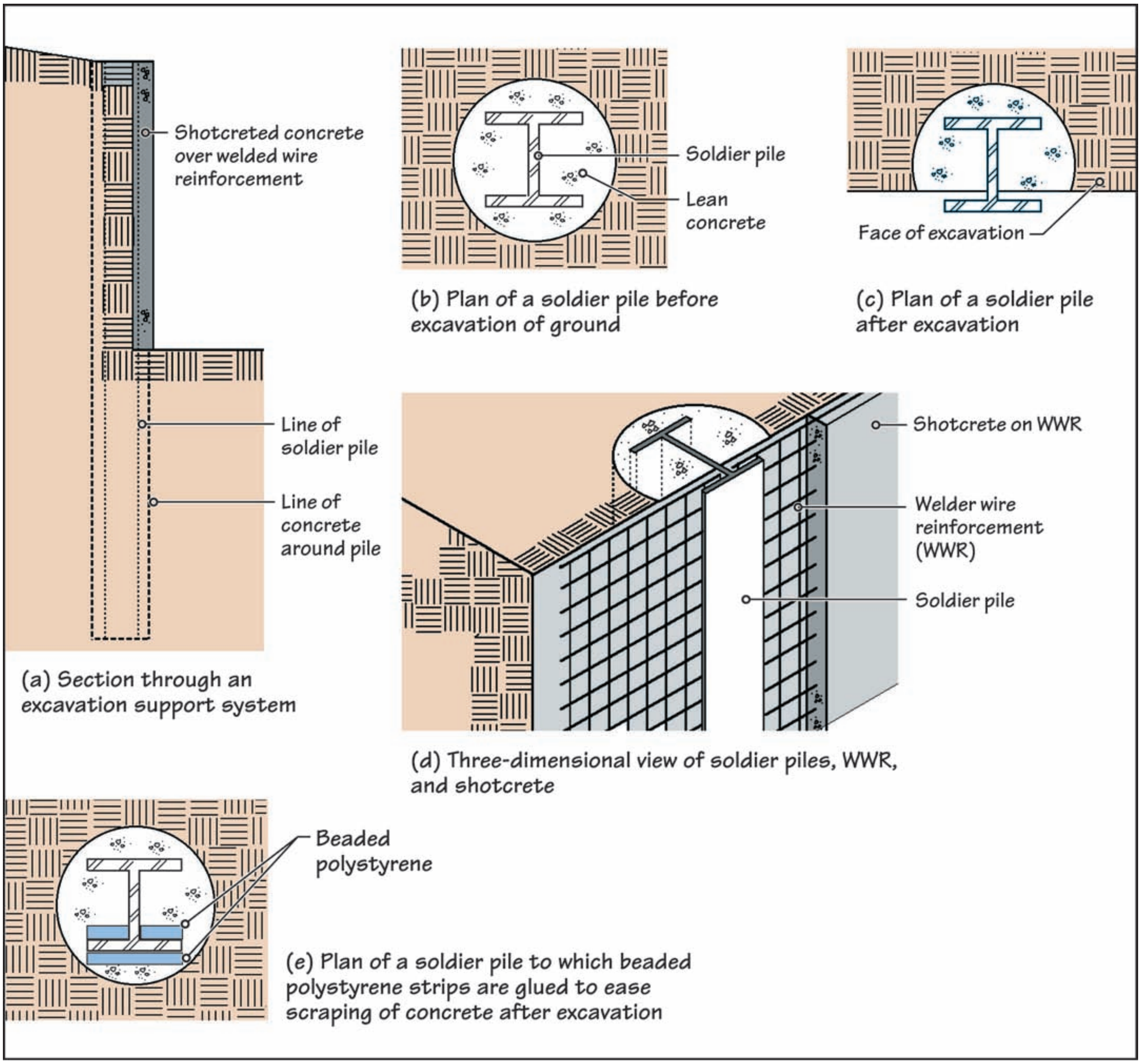
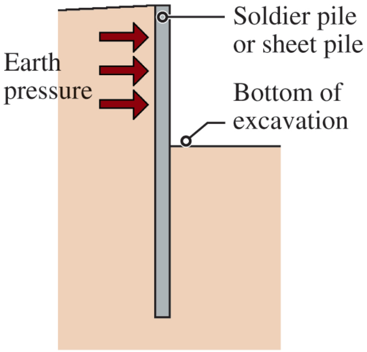

Shotcreted concrete over welded wire reinforcement
Line of soldier pile
Line of concrete around pile
(a) Section through an excavation support system
Soldier pile
Lean concrete
(b) Plan of a soldier pile before excavation of ground
Face of excavation
(c) Plan of a soldier pile after excavation
Shotcrete on WWR
Welder wire reinforcement (WWR)
Soldier pile
(d) Three-dimensional view of soldier piles, WWR, and shotcrete
Beaded polystyrene
(e) Plan of a soldier pile to which beaded polystyrene strips are glued to ease scraping of concrete after excavation

FIGURE 11.15 Steps showing the construction of cantilevered soldier pile excavation support with welded wire reinforcement (WWR) and shotcrete.


Earth pressure
Soldier pile or sheet pile
Bottom of excavation

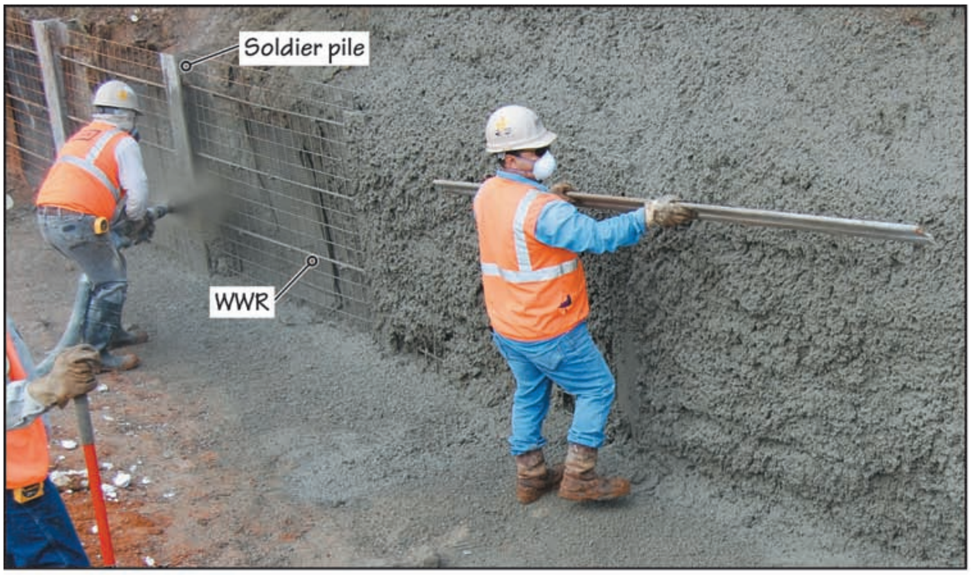
Soldier piles or sheet piles must penetrate sufficiently into the ground below the bottom of the excavation in order to resist earth pressure as vertical cantilevers.

the ground. The piles are placed in predrilled circular holes approximately 6 to 8 ft on center. After the piles are placed, the holes are filled with lean concrete (about 1,500 psi strength), Figure 11.15(b). Excavation of the ground abutting the piles is commenced after the concrete around the piles has gained sufficient strength.

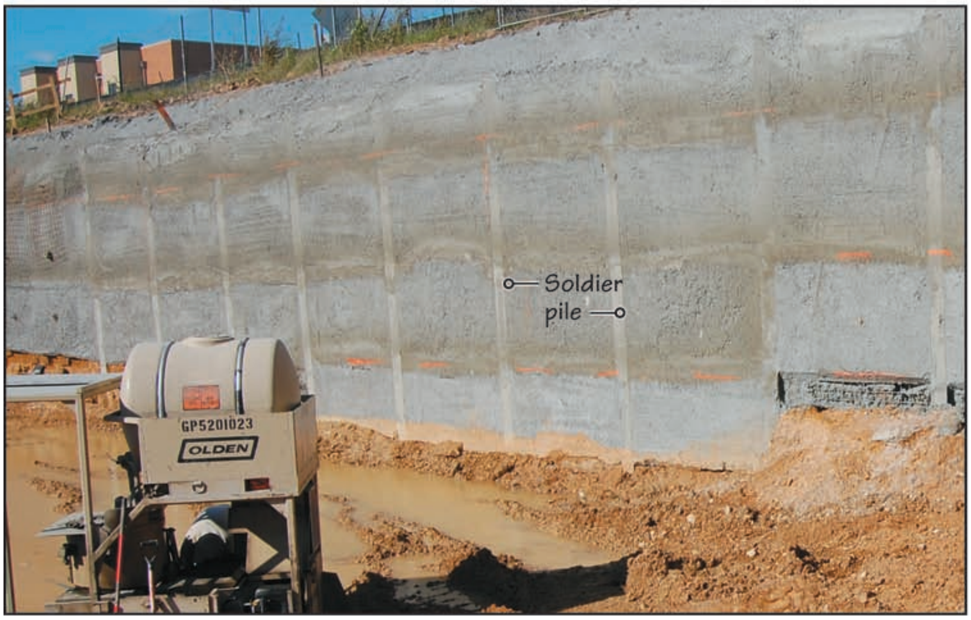
The ground is excavated in vertical segments 5 to 6 ft in height that expose the encased piles. Part of the concrete encasing the piles is now scraped to make way for the welded wire reinforcement (WWR) placed between the flanges of adjacent H-piles, Figures 11.15(c) and (d). The leanness of concrete allows the scraping to take place. Some earth retention contractors glue beaded polystyrene strips to the front and back sides of the outer flange of the piles to simplify the scraping of concrete, Figure 11.15(e). (See Section 21.13 for a discussion of WWR.)

After the WWR is placed, concrete is sprayed over the reinforcement under high velocity and pressure (referred to as *shotcrete* or *gunite*). The shotcreted concrete is floated to provide a smooth finish, Figure 11.16. Pressure-treated, rough-sawn horizontal lumber members, called *lagging*, are an alternative to shotcrete between soldier piles (see Figure 11.17).

Structurally, the shotcrete on WWR (or lumber lagging) between the adjacent piles functions as a wall that transfers earth pressure horizontally to the piles. The piles behave as vertical columns cantilevered from the ground. Therefore, like the sheet piles, soldier piles must be buried sufficiently below the bottom of the excavation to provide the required cantilever action, as shown in Figure 11.15(a).


Soldier pile
WWR

(a) Shotcreting over WWR and finishing of an already shotcreted part of a wall


Soldier pile
GP5201023
OLDEN

(b) A partially completed excavation support using soldier piles

FIGURE 11.16 Excavation support using cantilevered soldier piles.

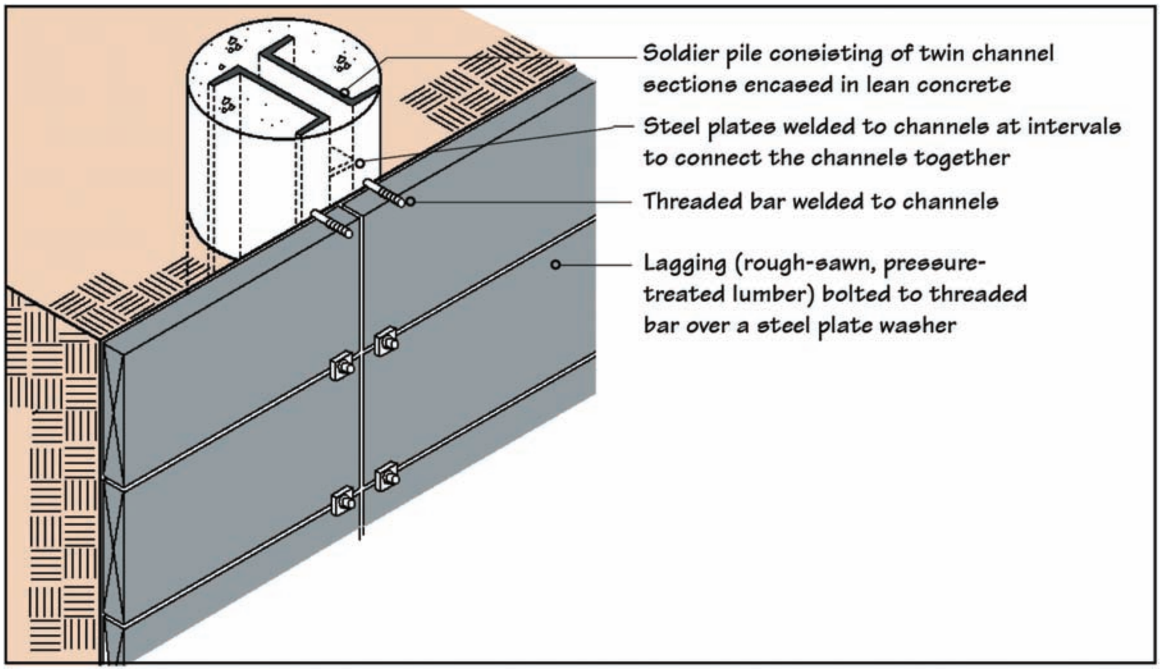

Soldier pile consisting of twin channel sections encased in lean concrete
Steel plates welded to channels at intervals to connect the channels together
Threaded bar welded to channels
Lagging (rough-sawn, pressure-treated lumber) bolted to threaded bar over a steel plate washer

FIGURE 11.17 Soldier pile support system with twin channel sections and lumber lagging between piles. Lumber lagging may be replaced by welded wire reinforcement and shotcrete.

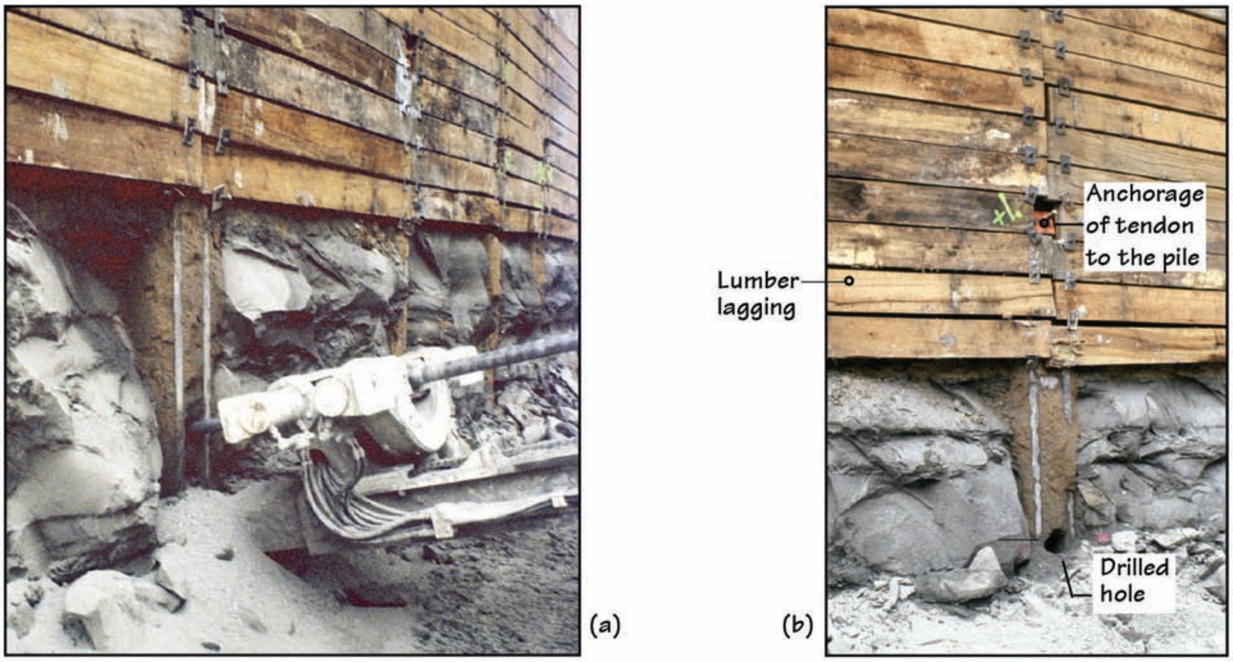

(a)
(b)
Lumber lagging
Anchorage of tendon to the pile
Drilled hole

FIGURE 11.18 **(a)** The hole for a tieback is drilled through the space between the twin steel channels comprising the pile**.** **(b)** A high-strength steel tendon is now placed into the hole, and the hole is filled with Portland cement–based grout. After the grout has gained sufficient strength, the tendon is stressed to the required tension and anchored to the pile as shown.

EXCAVATION SUPPORT USING ANCHORED SOLDIER PILES

The use of a cantilevered soldier pile system is uneconomical beyond a depth of approximately 15 ft because of the increase in pile cross section. For deeper excavations, an anchored soldier pile system is employed, which is similar to the cantilevered pile system except that the piles are tied back (anchored) into the ground. The commonly used vertical support members for this system consist of two steel channels with a space between them. The channels are connected together with steel plates welded at intervals in this space, Figure 11.17.

Drilling for tieback anchors is done through the space between the twin C-sections of piles, Figure 11.18. After a tieback hole has been drilled, steel bars or high-strength steel tendons are placed in the hole, and the hole is grouted, Figure 11.19. The bars or tendons are subsequently anchored to the piles, Figure 11.20. If high-strength steel tendons are used,

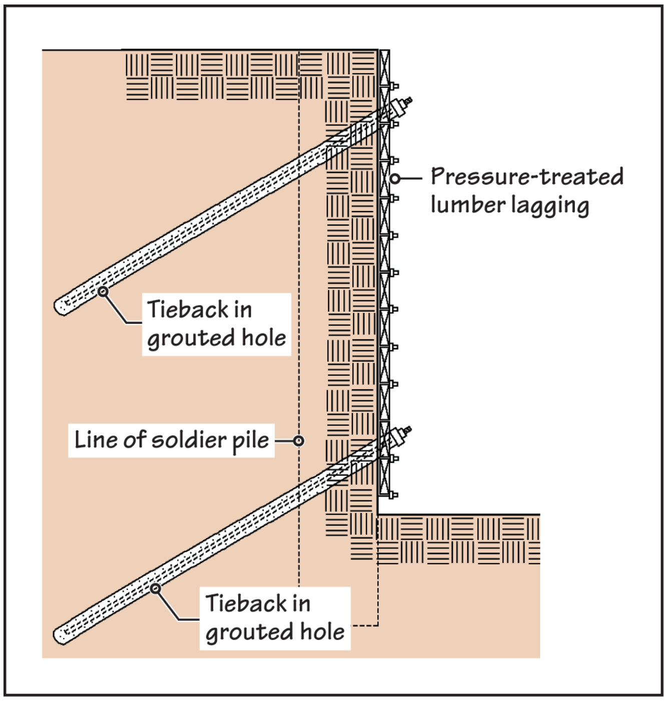

Pressure-treated lumber lagging
Tieback in grouted hole
Line of soldier pile
Tieback in grouted hole

FIGURE 11.19 Section through an anchored soldier pile support system with lumber lagging. Tiebacks are installed as the excavation proceeds. This is followed by bolting the lagging to the piles. The number of tiebacks required is a function of the depth of excavation and the type of soil.

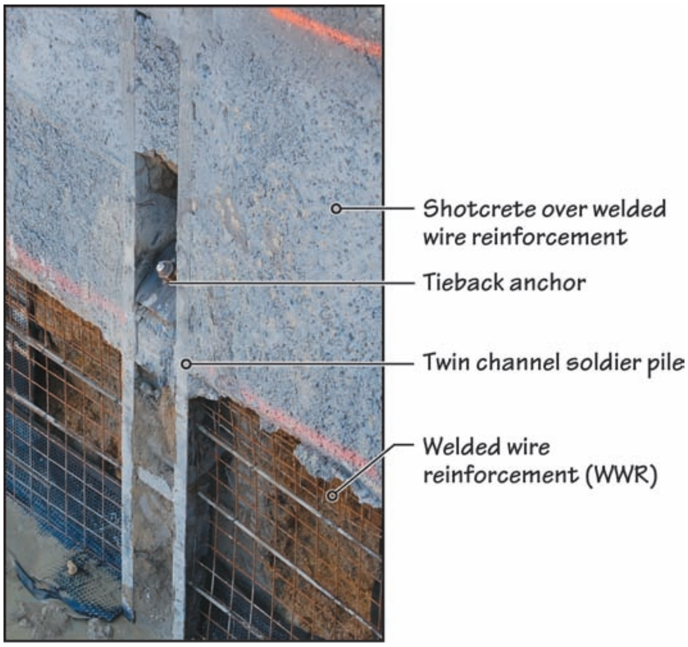

Shotcrete over welded wire reinforcement
Tieback anchor
Twin channel soldier pile
Welded wire reinforcement (WWR)

FIGURE 11.20 Tieback anchor detail in an anchored soldier pile support system with WWR and shotcrete.

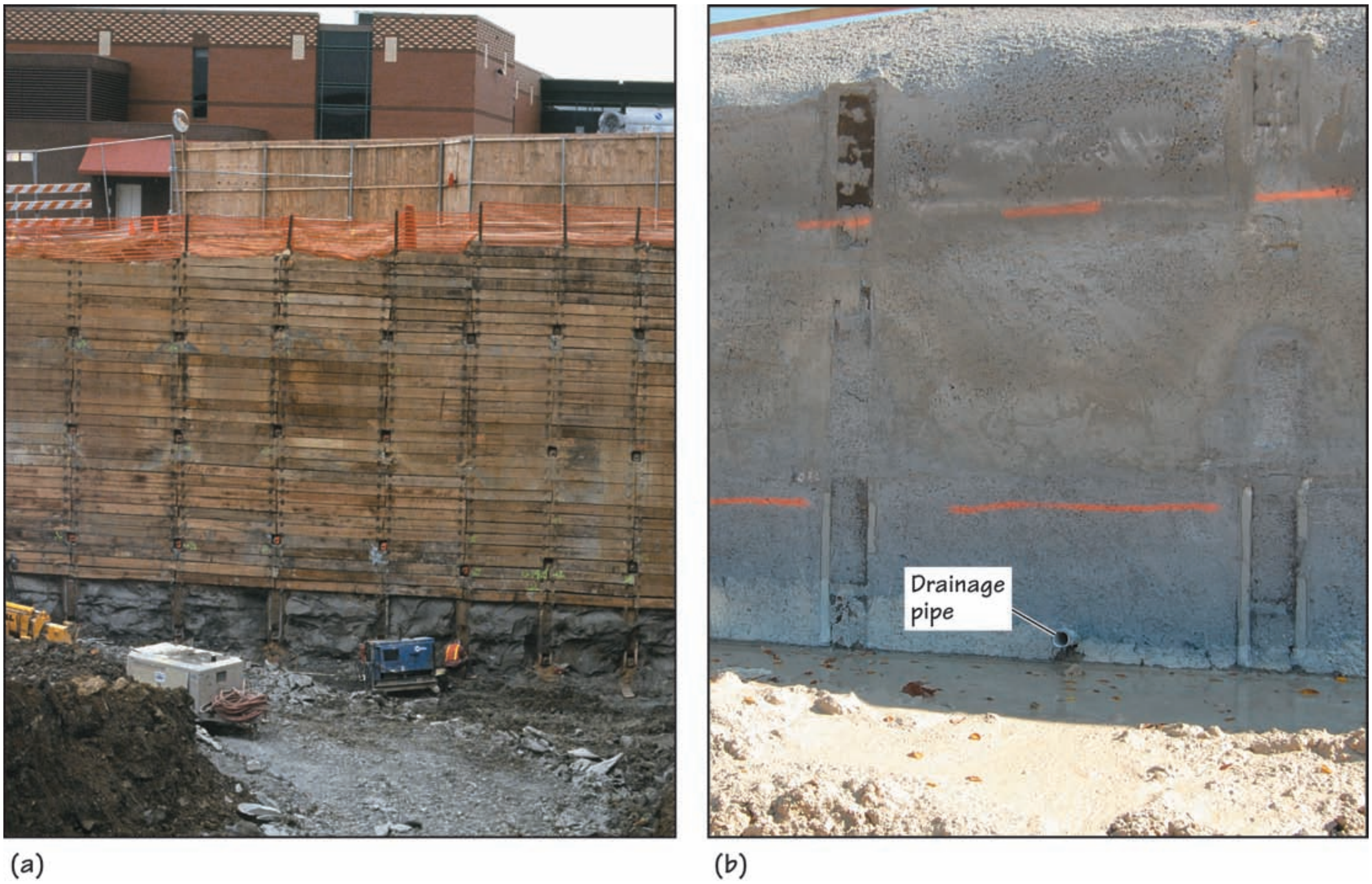


FIGURE 11.21 **(a)** Anchored pile excavation support system with lumber lagging. **(b)** Anchored pile excavation support system with shotcrete and welded wire reinforcement. Tieback anchors are not visible because they have been shotcreted over. The drainage pipe drains water from behind the support system. The water is collected in the sump located in the interior of the basement from where it is pumped out. All excavation support systems need such internal drainage.

pressure grouting of holes and posttensioning of tendons are done after the grout has gained strength. The soil in which posttensioned tiebacks are used must have adequate holding power to withstand the pull-out force on the tendons.

The earth retention between the anchored piles can be provided by shotcrete over WWR, as shown in Figure 11.20. Alternatively, pressure-treated lumber lagging, attached to the piles through threaded bolts, may be used (as shown in Figures 11.17 and 11.18). Overall views of anchored pile systems using both alternatives (lumber lagging and shotcrete over WWR) are shown in Figure 11.21.

Whereas the sheet pile method of excavation support is relatively water resistant, the soldier pile and lagging system allows a much greater amount of water to percolate through the lagging. Therefore, the pile system is used in situations where water percolation is relatively small. In both cases, however, dewatering of the excavation may be required to keep the excavation dry (see Section 11.7).

EXCAVATION SUPPORT USING CONTIGUOUS BORED CONCRETE PILES

In situations where the (deep) excavation is close to an adjacent building or the property line, tiebacks cannot be used. In this situation, closely spaced reinforced concrete piles, called *contiguous bored piles* (CBPs), are often used, Figure 11.22. Each pile is made by screwing an auger into the ground. The auger, called a *continuous flight auger*, has a hollow stem in the middle of a continuous spiral drill.

Once the drill has reached the required depth below the ground, high-slump concrete is pumped down the hollow stem of the auger to the bottom of the bore. Once the pumping starts, the auger is progressively withdrawn. The withdrawing auger brings the soil from the bore to the surface, where it is removed. Thus, the sides of the bore are supported at all times by the

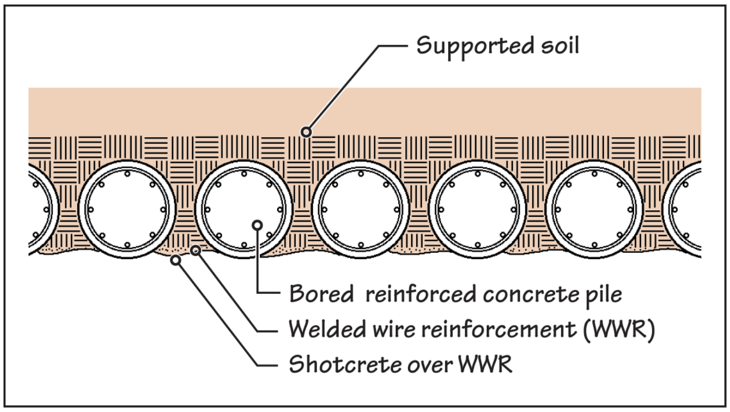

Supported soil
Bored reinforced concrete pile
Welded wire reinforcement (WWR)
Shotcrete over WWR

FIGURE 11.22 Closely spaced drilled (bored) concrete piles shown in plan.

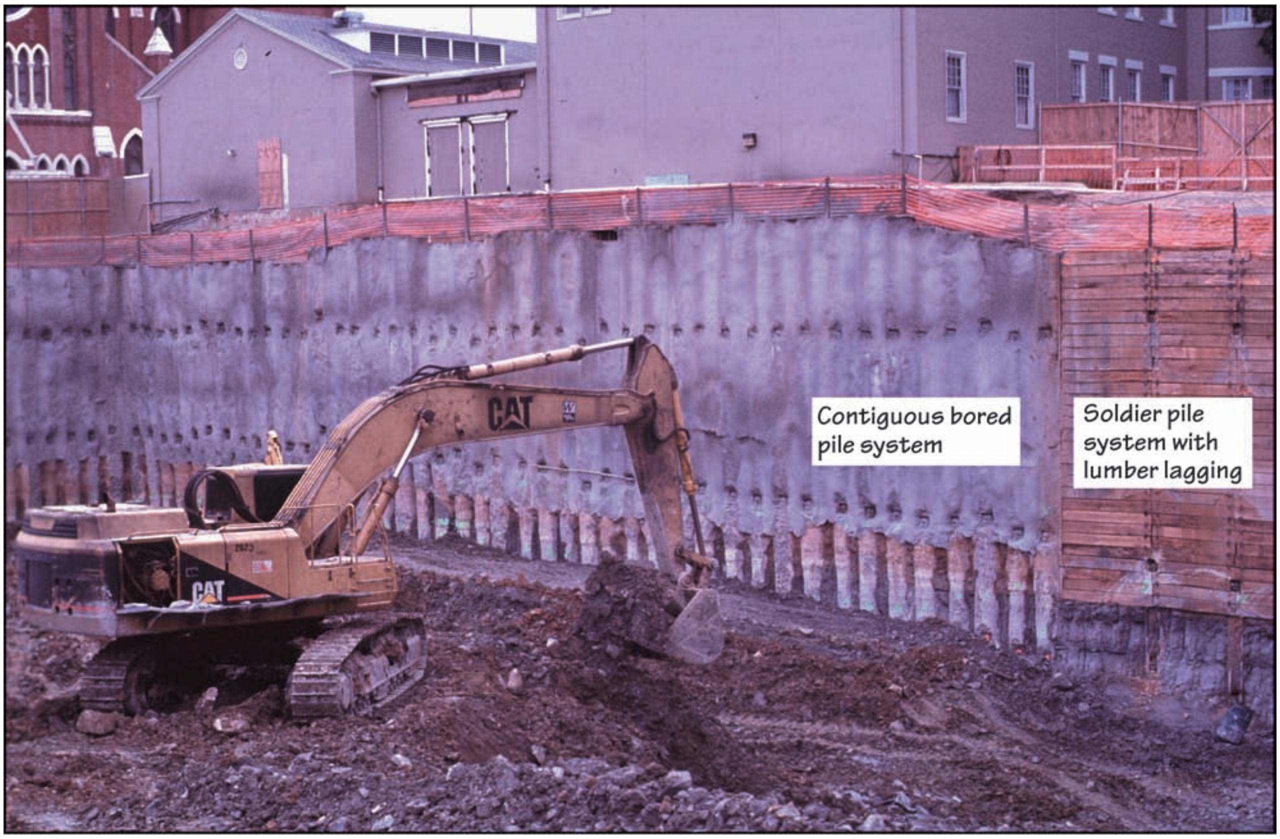

Contiguous bored pile system
Soldier pile system with lumber lagging

FIGURE 11.23 Contiguous bored piles used as supports for a deep basement excavation in a tight urban location. In areas farther away from the existing building or property line, the soldier pile and lagging system is used. Note that as the excavation proceeds, the lower part of drilled concrete piles will also be shotcreted as shown here for the upper part.

soil-filled auger or concrete. Immediately after the entire bore has been concreted, a reinforcement cage is lowered in the concrete-filled bore.

The depth of CBPs is limited by the length of the reinforcement cage that can be lowered through the concrete. (The reinforcement cage is specially designed to have adequate stiffness to penetrate into fresh concrete.) CBPs up to 100 ft deep have been constructed. They are generally 18 in. to 36 in. in diameter, depending on the depth of the excavation.

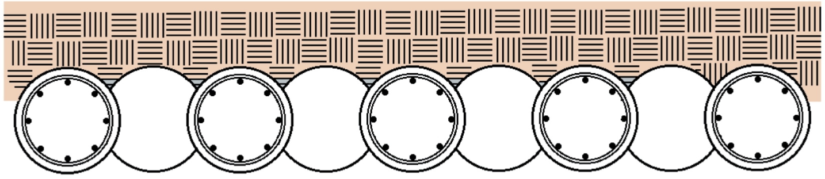
After the piles have been constructed and the excavation proceeds, the piles and the (small) soil spaces between them are shotcreted to reduce water percolation through the cut face, Figure 11.23.

EXCAVATION SUPPORT USING SECANT PILES

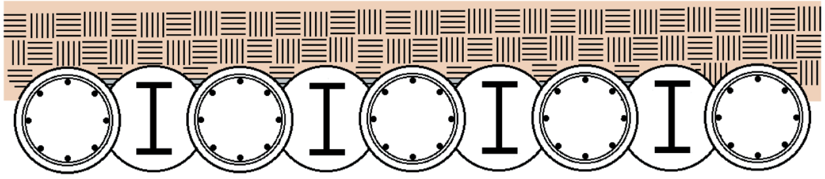
A major shortcoming of CBPs is the gaps between piles and the consequent lack of water resistance of the excavation support. This problem is overcome by the use of the modified version of CBPs called *secant piles*.

Secant piles essentially consist of two sets of interlocking contiguous piles. The first set, called the *primary piles*, is bored and concreted in the same way as the CBPs. The center-to-center distance between the primary piles is slightly smaller than twice their diameter.

After the primary piles are constructed, the *secondary piles* are bored at mid-distance between the primary piles, which also bores through part of the primary piles, Figure 11.24(a). The boring for secondary piles is done before the concrete in the primary piles has gained full strength to reduce wear on the blades of the auger. The secondary piles are concreted and reinforced in the same way as the CBPs. In most situations, only the secondary piles are reinforced, Figure 11.24(a). This precludes accidental cutting of any misaligned reinforcement in the primary piles. Thus, the unreinforced primary piles provide a water-resistant layer between the secondary piles.



(a) Secant piles with unreinforced primary piles



(b) Secant piles with reinforced primary piles

FIGURE 11.24 Excavation support through secant piles.

Where greater bending strength of the support system is required, the primary piles are also reinforced, generally with a wide-flange steel section, and the secondary piles are reinforced with a circular steel reinforcement cage, Figure 11.24(b).

EXCAVATION SUPPORT USING SOIL NAILING

Soil nailing is a means of strengthening the soil with closely spaced, inclined steel bars that increase the cohesiveness of the soil and prevent the soil from shearing along an inclined plane. The inclined bars are almost perpendicular to the possible shearing plane. In other words, the steel bars connect imaginary inclined layers of the earth into a thick block that behaves as a gravity-retaining wall when excavated, Figure 11.25.

The process of soil nailing consists of the following steps:

- The soil is first excavated 5 ft to 7 ft deep, depending on the ability of the cut face to remain vertical without supports.
- Holes are drilled along the cut face at 3 ft to 4 ft on centers so that one hole covers approximately 10 ft^2 to 15 ft^2 of the cut face, Figure 11.26(a).
- Threaded steel bars (approximately 1 in. in diameter) are inserted in the holes. The length of the bars is a function of the soil type but is approximately half the final depth of excavation. The bars protrude a few inches out of the holes.
- The holes are grouted with concrete, Figure 11.26(b).
- WWR is placed over the wall and tied to the protruding bars.
- A layer of shotcrete is applied to the mesh.
- Plates and washers are inserted in the protruding bars and locked in position with a nut.
- A second layer of shotcrete may be used if the soil-nailed wall is the finished wall, or a cast-in-place concrete wall may be constructed against it.
- These steps are repeated with the next depth of cut.

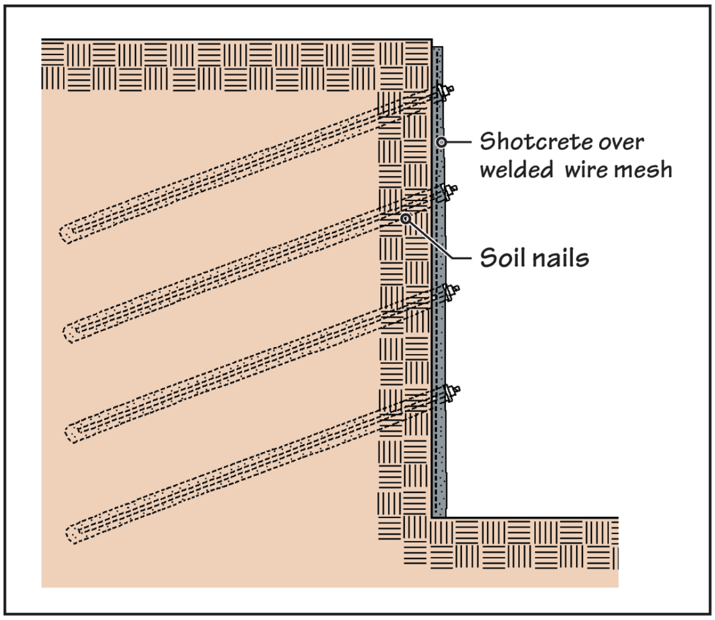


FIGURE 11.25 Section through a soil-nailed excavation support.

Figure 11.27 shows a soil-nailed wall that is almost complete. Note that soil nails are not posttensioned.

EXCAVATION SUPPORT USING BENTONITE SLURRY AS TRENCH SUPPORT

Another excavation support system, commonly used in situations where the underground water table is relatively high, is a reinforced concrete wall. Construction of such walls is done by excavating 10-ft to 15-ft-long discontinuous trench sections down to bedrock, called

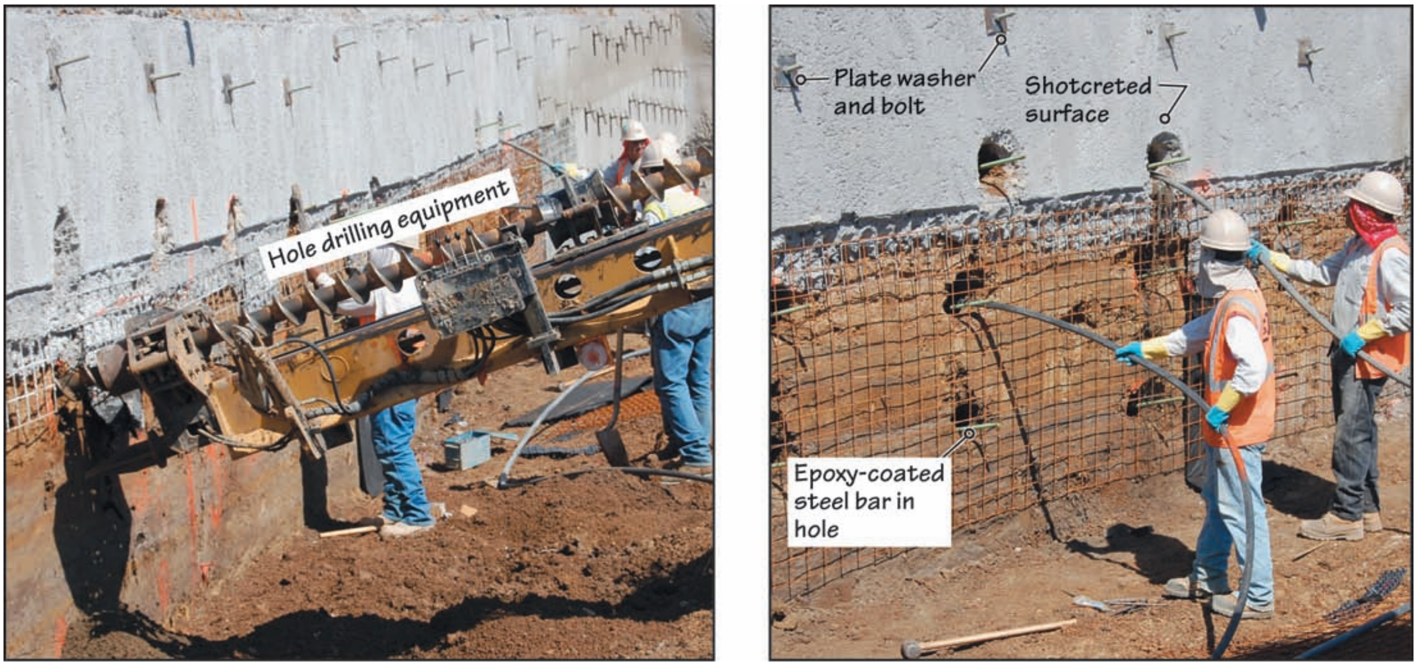


FIGURE 11.26 **(a)** Drilling of holes in excavated soil. **(b)** Grouting of holes after the epoxy-coated steel bar (soil nail) has been placed in the drilled holes.

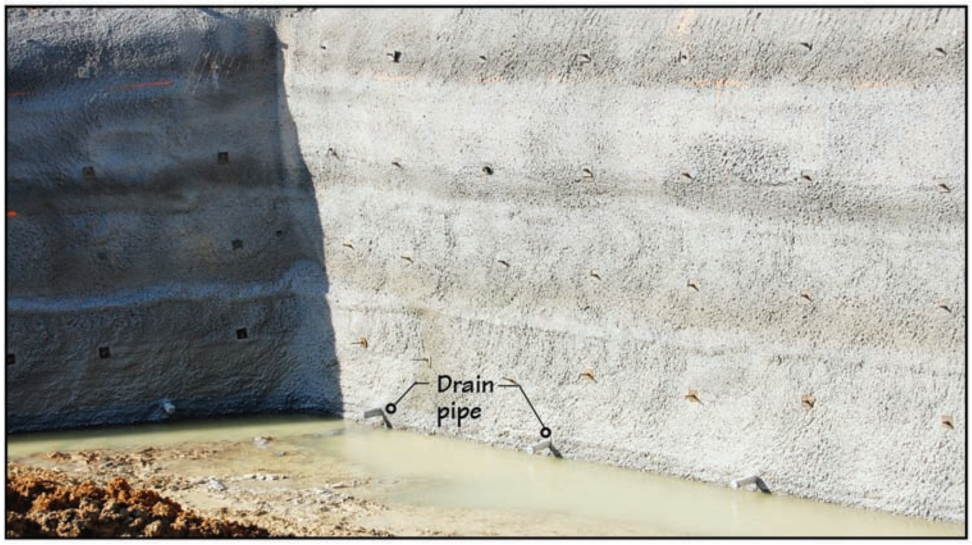


FIGURE 11.27 View of a completed soil-nailed excavation support. Note the drain pipes, as all excavation support walls require drainage outlets in order to reduce pressure on the wall from the wet soil behind (see also Figure 11.11).

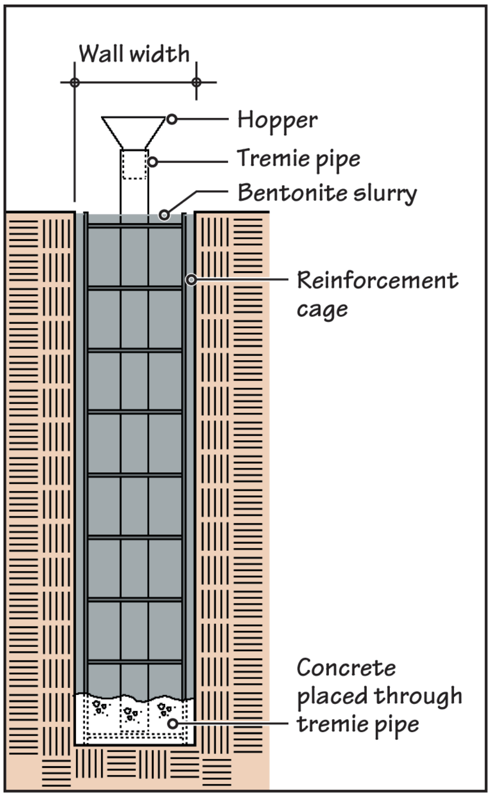


FIGURE 11.28 Trench support through bentonite slurry.

primary panels. The width of the trench sections is the required thickness of the concrete wall. So that the soil does not collapse, the trench is continuously kept filled with bentonite slurry as the excavation proceeds. (Bentonite slurry is a mixture of water and bentonite clay, which pressurizes the walls of the trench sufficiently to prevent their collapse during excavation.)

Special excavation equipment is used to extract soil through the slurry-filled trench. After the excavation for the entire primary panel is complete, a reinforcement cage is lowered into the trench. Concrete is then placed in the trench panel using two or more *tremie pipes*, typically one at each end of the panel. Concrete is placed from the bottom up, and the discharge end of the tremie is always buried in concrete. A tremie pipe is generally an 8-in. to 10-in.-diameter steel pipe with a hopper at the top, Figure 11.28.

As concreting proceeds, the slurry is pumped out from the top of the trench and stored for later use. After the primary panels have been constructed, excavation for secondary panels (between the primary panels) is undertaken in the same way as for the primary panels. To provide shear key and water resistance between primary and secondary panels, a steel pipe is embedded at the end of each primary panel prior to its concreting. These pipes are removed after the concrete in the primary panels has gained sufficient strength.

The tremie pipe method of concrete placement requires great care and expertise, particularly the initial placement of concrete, which is generally a richer mix. The concrete must also be placed slowly so that it does not get too diluted by the slurry.

11.7 KEEPING EXCAVATIONS DRY

It is important to keep excavations free from groundwater. Even a small amount of water saturation in excavated areas impedes further excavation, is unsafe for workers, and is harmful to equipment and machines. Additionally, if the amount of groundwater is reduced, so is the pressure exerted by the soil on excavation supports—sheet piles, soldier piles, and so on.

Groundwater control in an excavation consists of two parts: (a) preventing surface water from entering the excavation through runoff and (b) draining (dewatering) the soil around the excavations so that the groundwater level falls below the elevation of proposed excavation. Two commonly used methods of dewatering the ground are *sump pumps* and *well points*.

DEWATERING THROUGH SUMPS

Sump dewatering consists of constructing pits (called *sumps*) within the enclosure of the excavation. The bottom of sumps must be located below the final elevation of the excavation. As the groundwater from surrounding soil percolates into the sump, it is lifted by automatic pumps and discharged away from the building site, Figure 11.29. The number of required sumps is a function of the excavation area. The method of discharge of pumped water must meet with the approval of local authorities.

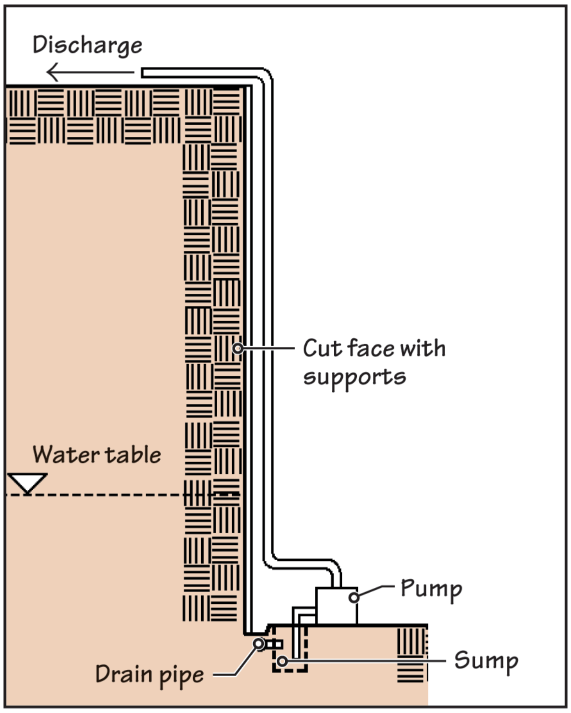


FIGURE 11.29 Sumps for groundwater control in an excavation.

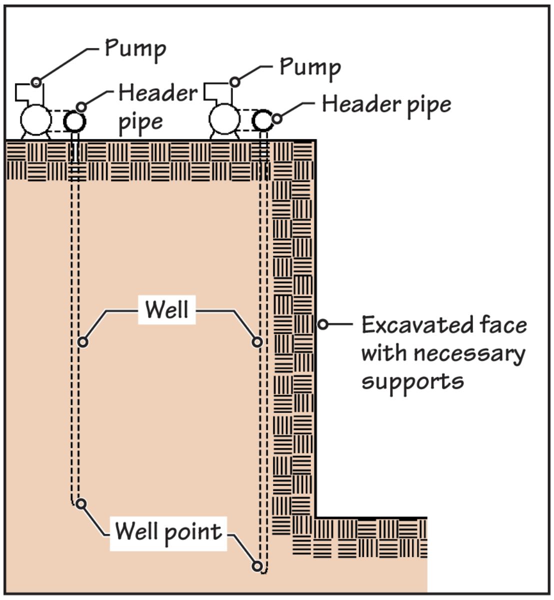


FIGURE 11.30 Section through an excavation showing two rings of well points.

DEWATERING THROUGH WELL POINTS

Sump dewatering works well in cohesive soils, where the percolation rate is slow and where the water table is not much higher than the final elevation of the base of the excavation. A more effective dewatering method uses forced suction to extract groundwater. This is done by sinking a number of vertical pipes with a screened end at the bottom (called *well points*) around the perimeter of the excavation. The well points reach below the floor of the excavation and are connected to large-diameter horizontal header pipes at the surface.

The header pipe is connected to a vacuum-assisted centrifugal pump that sucks water from the ground for discharge to an appropriate point. For a very deep excavation, two rings of well points may be required. The well points in the ring farther away from the excavation terminate at a higher level than those close to the excavation, Figure 11.30.

Whereas the sump method of dewatering does not greatly affect the existing water table, dewatering by well points can lower the water table considerably. The effect of this on the adjoining buildings must be considered because it can cause consolidation and settling of the foundations of existing buildings on some types of soils.

Dewatering of excavations can be fairly complicated and generally requires an expert dewatering subcontractor for large and complicated operations.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

15. Grading at a site refers to
- **a.** evaluating the existing subsurface conditions of a site.
- **b.** evaluating the groundwater conditions at a site.
- **c.** compacting the soil to required density.
- **d.** all of the above.
- **e.** none of the above.

16. Engineered fill refers to the soil that is
- **a.** specially formulated to provide the required properties.
- **b.** placed per the geotechnical engineer's specifications.
- **c.** compacted per the geotechnical engineer's specifications and inspection.
- **d.** all of the above.
- **e.** none of the above.

17. A benched excavation is generally used
- **a.** on open suburban sites.
- **b.** on tight downtown sites.
- **c.** where the excavation depth is less than 5 ft.
- **d.** where dewatering of the site is not required.

18. Sheet piles are used
- **a.** as shallow foundations in buildings.
- **b.** as deep foundations in buildings.
- **c.** as formwork for concrete walls.
- **d.** as excavation supports.
- **e.** none of the above.

19. Which of the following is not used for excavation supports?
- **a.** Sheet piles
- **b.** Soldier piles
- **c.** Soil nailing
- **d.** Precast concrete piles
- **e.** Contiguous bored concrete piles

20. In the excavation support system using soldier piles, the soldier piles consist of
- **a.** sheet steel.
- **b.** sheet aluminum.
- **c.** structural steel sections.
- **d.** reinforced concrete.
- **e.** precast concrete.

21. In the soldier pile and lagging system, the lagging generally consists of
- **a.** pressure-treated lumber.
- **b.** pressure-treated plywood.
- **c.** structural steel sections.
- **d.** sheet steel.
- **e.** none of the above.

(*Continued*)

PRACTICE QUIZ *(Continued)*

22. An alternative to lagging that is commonly used with the soldier pile system of excavation support is
- **a.** pressure-treated lumber.
- **b.** pressure-treated plywood.
- **c.** structural steel sections.
- **d.** sheet steel.
- **e.** shotcrete over welded wire reinforcement (WWR).

23. Tiebacks used with the anchored soldier pile system of excavation support consist of
- **a.** prestressing tendons in grouted holes.
- **b.** structural steel angle sections in grouted holes.
- **c.** reinforcing steel bars in grouted holes.
- **d.** prestressing tendons or reinforcing steel bars in grouted holes.
- **e.** none of the above.

24. Contiguous bored piles are constructed using
- **a.** structural steel sections.
- **b.** site-cast reinforced concrete.
- **c.** precast concrete.
- **d.** precast, prestressed concrete.
- **e.** none of the above.

25. In terms of design and construction, secant piles are related to
- **a.** sheet piles.
- **b.** soldier piles.
- **c.** contiguous bored piles.
- **d.** none of the above.

26. The center-to-center distance between secant piles is generally
- **a.** 5 to 8 ft.
- **b.** 8 to 12 ft.
- **c.** 10 to 15 ft.
- **d.** 15 to 20 ft.
- **e.** none of the above.

27. Soil nailing refers to
- **a.** a cut face of excavation supported by closely spaced steel bars or angles.
- **b.** a cut face of excavation supported by closely spaced steel bars and shotcrete.
- **c.** a cut face of excavation supported by closely spaced steel bars and shotcrete over WWR.
- **d.** a cut face of excavation supported by closely spaced steel bars in grouted holes and shotcrete over WWR.
- **e.** none of the above.

28. Dewatering of an excavation, as described in this text, can be done by the
- **a.** pit method.
- **b.** sump method.
- **c.** well-point method.
- **d.** (a) and (b).
- **e.** (b) and (c).

PRINCIPLES IN PRACTICE

Unified Soil Classification

The soil's classification (into gravel, sand, silt, and clay), described in Section 11.1, is too broad to be useful in building construction, because subsurface deposits containing pure gravel, pure sand, and so on, are extremely rare. Generally, we find soil mixtures that contain two or more of the four soil materials in varying proportions. Therefore, a more detailed classification is required. The classification commonly used is called the *Unified Soil Classification System* (USCS). In the USCS, the distinction between coarse- and fine-grained soils is as follows.

Coarse-grained soils are soils that contain more than 50% of material retained on a No. 200 sieve. Coarse-grained soils are further subdivided into *gravelly soils* and *sandy soils*. Gravelly soils are those in which 50% or more of the coarse fraction is retained on a No. 4 sieve. In sandy soils, more than 50% of the coarse fraction passes through a No. 4 sieve.

Gravelly soils are further subdivided into *clean gravels* and *dirty gravels*. Similarly, sandy soils are further subdivided into *clean sands* and *dirty sands*.

Fine-grained soils are soils that contain 50% or more of material passing through a No. 200 sieve. Fine-grained soils are further subdivided into Group L soils and Group H soils. This distinction is based on the plasticity of the soil, which is measured by the soil's *liquid limit*. A soil with *low* plasticity (liquid limit $\leq 50\%$) belongs to Group L soils. A soil with *high* plasticity (liquid limit $> 50\%$) is classified as a Group H soil.

Additional details of USCS are given in Table 11.P1.

SYMBOLS USED IN THE USCS

USCS uses the following symbols to designate various soils:

G for gravel
S for sand
M for silt
C for clay

W for well-graded particles, that is, when particles of various sizes are present, giving a relatively denser soil

P for poorly graded soils, that is, soils with a very little (i.e., almost uniform) gradation of particle sizes. (Such soils contain more void space and are, therefore, less dense.)

PRINCIPLES IN PRACTICE

TABLE 11.P1 UNIFIED SOIL CLASSIFICATION SYSTEM (USCS)

Major divisions			**Group symbols**	**Group description**
Coarse-grained soils **>50% material retained on No. 200 sieve**	**Gravelly soils** >50% of coarse fraction retained on No. 4 sieve	**Clean gravels** Fines <5%	**GW**	Well-graded gravels and gravel-sand mixtures, little or no fines
		In field test, no stain on wet palm	**GP**	Poorly graded gravels and gravel-sand mixtures, little or no fines
		Dirty gravels Fines >12%	**GM**	Silty gravels, gravel-sand-silt mixtures
		In field test, stain on wet palm	**GC**	Clayey gravels, gravel-sand-clay mixtures
	Sandy soils ≥50% of coarse fraction passes through No. 4 sieve	**Clean sands** Fines <5%	**SW**	Well-graded sands and gravelly sands, little or no fines
		In field test, no stain on wet palm	**SP**	Poorly graded sands and gravelly sands, little or no fines
		Dirty sands Fines >12%	**SM**	Silty sands, sand-silt mixtures
		In field test, stain on wet palm	**SC**	Clayey sands, sand-clay mixtures
Fine-grained soils **≥50% material passes through No. 200 sieve**	**Silts and clays** Liquid limit ≤50%		**ML**	Inorganic silts, very fine sands, rock flour, silty or clayey fine sands
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
			OL	Organic silts and organic silty clays of low plasticity
	Silts and clays Liquid limit >50%		**MH**	Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts
			CH	Inorganic clays of high plasticity, fat clays
			OH	Organic clays of medium to high plasticity
Highly Organic Soils			**Pt**	Peat, muck, and other highly organic soils

Note: Gravelly or sandy soils with fines between 5% and 12% carry a hyphenated designation such as GW-GM, GW-GC, and so on.
Source: Adapted from Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)," ASTM D2487. Published by American Society for Testing and Materials (ASTM).

L for low plasticity (liquid limit ≤50%)
H for high plasticity (liquid limit >50%)
O for organic soils

Two symbols are used in conjunction to designate a soil. Thus, GW designates a well-graded gravel, GP designates a poorly graded gravel, ML designates a silty soil with a liquid limit less than or equal to 50%, and so on.

PLASTIC LIMIT AND LIQUID LIMIT OF FINE-GRAINED SOILS

The liquid limit of soil (a measure of the soil's plasticity) indicates the behavior of soil in the presence of water. If we take a sample of completely dry fine-grained soil and put a little water in it, it will become slightly moist, or semidry.

If the amount of water in the soil sample is increased, it will become plastic (puttylike), implying that it can be rolled into a rope between the palms of both hands. The ratio of the weight of water to the dry weight of the soil (expressed as a percentage moisture content) when a soil just changes from a semidry state to the plastic state is called the *plastic limit* (PL) of the soil.

If we keep adding water to the soil sample, a stage is reached when the soil loses its plasticity and turns into a slurry, that is, a liquid, Figure 11.31. The moisture content of soil when it just turns into a liquid is called its *liquid limit* (LL).

Gravels and sands do not become plastic. They change from a solid state to a liquid state. That is why the LL and PL concepts apply only to fine-grained soils—silts and clays.

(Continued)

Unified Soil Classification (*Continued*)

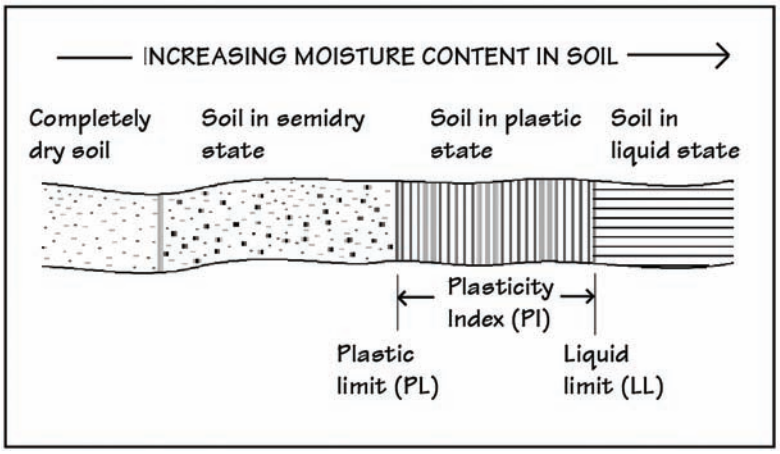


FIGURE 11.31 Four states of a fine-grained soil with increasing moisture content.

Another important soil property is the plasticity index (PI), defined as:

$PI = LL - PL$

For example, if a soil has a PL of 35% and an LL of 60%, its PI is $60 - 35 = 25\%$. Between two soils with the same LL, the one with the larger PI value retains more water and is, therefore, more susceptible to swelling and shrinkage due to changes in moisture.

EXPANSIVE SOILS

Some fine-grained soils expand with an increase in moisture content and shrink when the moisture content decreases. Foundations in such soils, referred to as *expansive soils*, are constructed to ensure that the structure is not adversely affected by soil movement.

A rough guide to the swell-shrink susceptibility of a fine-grained soil is provided by the following indices:

Highly expansive soil (high swell-shrink potential): LL >50% and PI >30%.

Medium expansive soil (medium swell-shrink potential): LL between 25% and 50% and PI between 15% and 30%.

Stable soil (low swell-shrink potential): LL <25% and PI <15%.

Expansive soils are found in many regions of the United States, such as California, Nevada, Texas, Arizona, and Maryland.

TESTING FOR LIQUID LIMIT OF FINE-GRAINED SOILS

A liquid-limit testing apparatus consists of a metal cup mounted on a hard rubber base, Figure 11.32. The motor attached to the cup raises it to a prescribed height and releases it for a free fall on the rubber base.

To determine the LL, the soil specimen is mixed with different amounts of water to give several batches of the specimen. A batch is placed in the cup and flattened to the required spread and thickness in the prescribed manner. A groove is then cut in the flattened batch with a standard grooving tool (shown in the foreground in Figure 11.32).

The number of falls of the cup that close the groove in a batch are recorded. A graph relating the moisture content of the soil with the number of falls for each batch is plotted. From this graph, the LL is obtained by reading the amount of moisture content that would be required to close the groove with 25 falls.

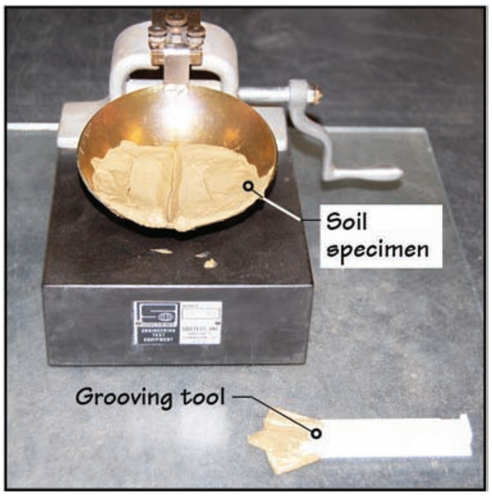


FIGURE 11.32 A liquid-limit testing apparatus.

TESTING FOR PLASTIC LIMIT OF FINE-GRAINED SOILS

A plastic-limit test involves taking a prescribed weight of dry sample and mixing it with water until it is almost saturated. The sample is rolled back and forth between two plastic plates until a thread nearly $\frac{1}{4}$ in. in diameter is formed, Figure 11.33(a).

PRINCIPLES IN PRACTICE

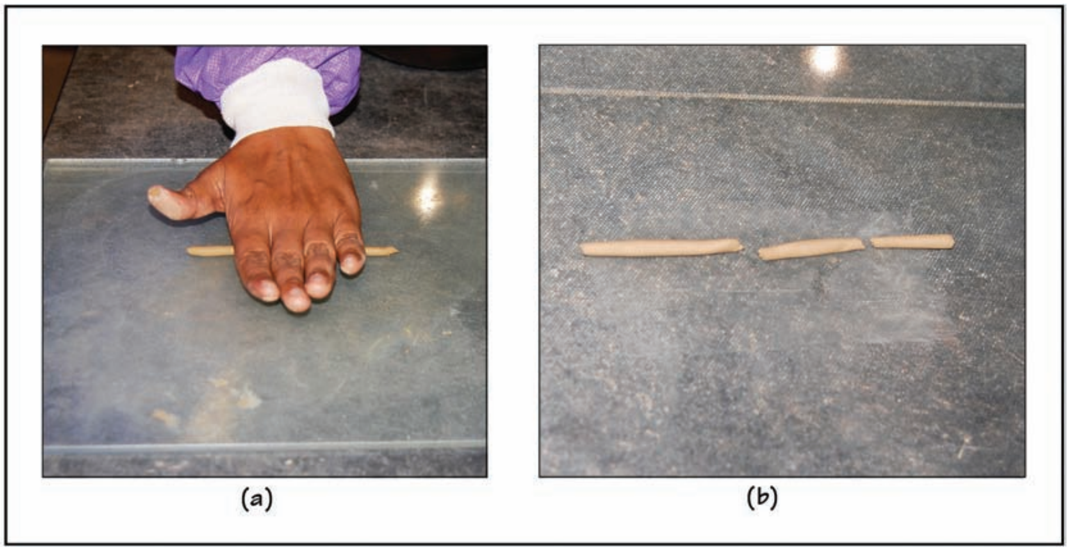


FIGURE 11.33 **(a)** Rolling moist soil into a thread. **(b)** As the moist soil thread is progressively dried while rolling, it breaks into short lengths.

The thread is then balled up and rolled again and again. Each rolling operation is performed under a fan so that the specimen gets progressively drier. A stage is reached when the thread breaks into short lengths, Figure 11.33(b). The broken soil threads are weighed by collecting them in a preweighed container (Figure 11.34) to determine the weight of wet soil threads. The threads are then fully dried in an oven and weighed again. From the difference between the weights, the moisture content of the soil is determined, which gives the PL of the soil.

Note that both the LL and PL tests are performed on the fraction of fine-grained soils that passes through a No. 40 sieve.

FIGURE 11.34 The broken threads of soil specimen are put in a container and weighed. They are then fully dried and weighed again. From the difference between the two weights, the soil's percentage moisture content is obtained, which is the PL of the soil.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

29. In the Unified Soil Classification System, the symbol M stands for
- **a.** medium-grained soil.
- **b.** moist soil.
- **c.** soil of medium plasticity.
- **d.** none of the above.

30. In the Unified Soil Classification System, the symbol GP stands for
- **a.** poorly graded gravel.
- **b.** pea gravel.
- **c.** peat and gravel.
- **d.** soil with good performance.
- **e.** none of the above.

31. Which of the following soils has the lowest liquid limit?
- **a.** Clay
- **b.** Silt
- **c.** Sand
- **d.** Mixture of silt and clay
- **e.** Mixture of silt and sand

32. The expansiveness of a soil is determined from the values of
- **a.** plastic limit and liquid limit.
- **b.** liquid limit and plasticity index.
- **c.** plastic limit and plasticity index.
- **d.** none of the above.

REVIEW QUESTIONS

1. Explain what is included in surface investigation and subsurface investigation of a site.
2. Explain the difference among (a) fine-grained soils and coarse-grained soils, (b) sand and gravel, and (c) silt and clay.
3. Explain why clayey soils are unstable.
4. Explain the difference between how a stiff, dense soil and a soft, loosely compacted soil perform during an earthquake.
5. Explain why the wall and column footings must be placed below the frost line.
6. Explain where self-supporting basement excavation may be used.
7. List various excavation support systems commonly used.
8. List the steps needed in the construction of a soil-nailed excavation support system.
9. Using sketches, explain the difference between cantilevered soldier pile and anchored soldier pile excavation support systems.

CHAPTER 12

Below-Grade Construction (Foundation Systems and Basements)

CHAPTER OUTLINE

12.1 SHALLOW FOUNDATIONS

12.2 DEEP FOUNDATIONS

12.3 PILES AS DEEP FOUNDATIONS

12.4 DRILLED PIERS AS DEEP FOUNDATIONS

12.5 FOUNDATION SETTLEMENT

12.6 FOUNDATION DRAINAGE

12.7 DETAILS OF FOUNDATION SYSTEMS ON STABLE SOILS

12.8 DETAILS OF FOUNDATION SYSTEMS ON EXPANSIVE SOILS

12.9 BASEMENT CONSTRUCTION AND WATERPROOFING

As shown in Figure 12.1, a building may be considered to comprise a: (a) superstructure, (b) substructure, and (c) foundation system. In this classification, the *superstructure* generally refers to the part of the building that is above the ground level. The *substructure* refers to basements, if provided, and the *foundation system* refers to the structure that lies below the substructure. Where a basement does not exist, a building has only a superstructure and foundations.

SHALLOW AND DEEP FOUNDATIONS

The choice of foundation type is governed by the characteristics of the soil near the surface and the pressure exerted on it by the loads on the building. Foundations are classified as shallow or deep. *Shallow foundations* extend a relatively short distance below the ground and bear directly on the upper soil stratum. Because of their lower cost, they are preferred over deep foundations. However, because the soil's bearing capacity is low at smaller depths from the surface, shallow foundations are generally limited to low- to mid-rise buildings.

Deep foundations are used where soil of adequate strength is not available close enough to the surface for the use of shallow foundations. Deep foundations consist of either piles or piers and are generally used for high-rise buildings. However, where the soil near the surface is unsuitable (e.g., subject to swell and shrink phenomenon), deep foundations are utilized for low-rise buildings as well so that the loads are transferred to a suitable stratum.

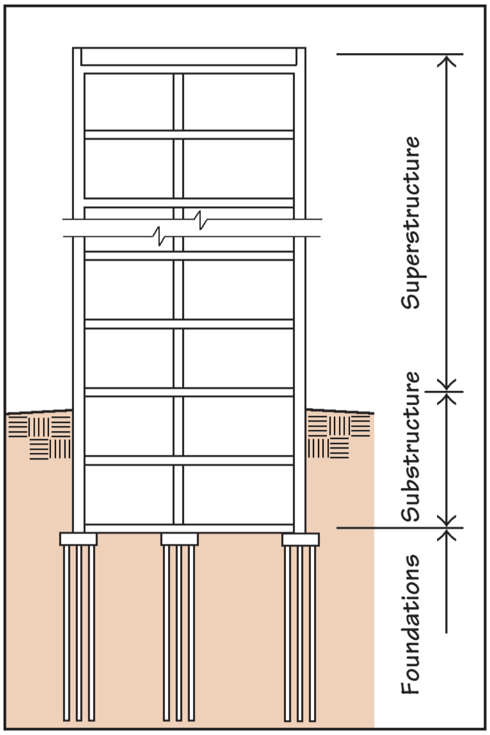


FIGURE 12.1 Three parts of a structure.

In other words, the choice of a foundation system for low- to mid-rise buildings is governed by the type of near-surface soil. If the near-surface soil is stable and has adequate strength, shallow foundations are appropriate. On the other hand, if the near-surface soil is either weak or unstable (i.e., expansive), deep foundations must be utilized. In the case of lightly loaded low-rise buildings, shallow foundations can be designed for use on expansive soils.

This chapter begins with a broad description of shallow and deep foundations, followed by a more detailed study of the systems. The study presented in Sections 12.7 and 12.8 classifies building foundation systems into two categories: (a) foundation systems on stable soils and (b) foundation systems on expansive soils. Most foundation systems suitable for expansive soils may also be used where near-surface soils have a low bearing capacity or are otherwise unsuitable.

NOTE

Foundation Failures due to Expansive Soils

As described in Section 11.1, expansive soils are present throughout the United States, but predominate in some states. Experts claim that damage to foundations not adequately designed for expansive soils totals several billion dollars in the United States every year. This damage receives little media attention because it is not life-threatening, like fires, earthquakes, hurricanes, and so on.

FOUNDATION MATERIALS

The materials commonly used for foundations are concrete (reinforced with either reinforcing steel or posttensioning tendons) and reinforced masonry (concrete masonry units). Less commonly used materials are plain (unreinforced) concrete, unreinforced masonry, and preservative-treated lumber and plywood. Our discussion is limited to reinforced concrete, posttensioned concrete, and reinforced masonry foundations.

12.1 SHALLOW FOUNDATIONS

There are two types of shallow foundations:

- Foundation systems consisting of footings (see Figure 12.2).
- Monolithic concrete foundation under the building's entire footprint (see Figure 12.4).

NOTE

Pier, Drilled Pier, and Bored Pier

The term *pier* in building construction generally means a column-like element that terminates a short distance above the ground and supports the structure above it. It may be of two types:

- A stub (short) masonry or concrete column constructed on a footing.
- A reinforced concrete column (buried in the soil) and supported on rock or firm soil deep in the ground. In this case, the pier is constructed by drilling a hole in the ground into which a steel reinforcement cage is lowered, followed by the placement of concrete in the hole.

To distinguish between the two types of piers, we have called the first type a *pier*, and the second type a *drilled pier* in this text. The terms *bored pier, bored pile,* and *caisson* are also used in place of *drilled pier*.

FOUNDATION SYSTEMS WITH FOOTINGS

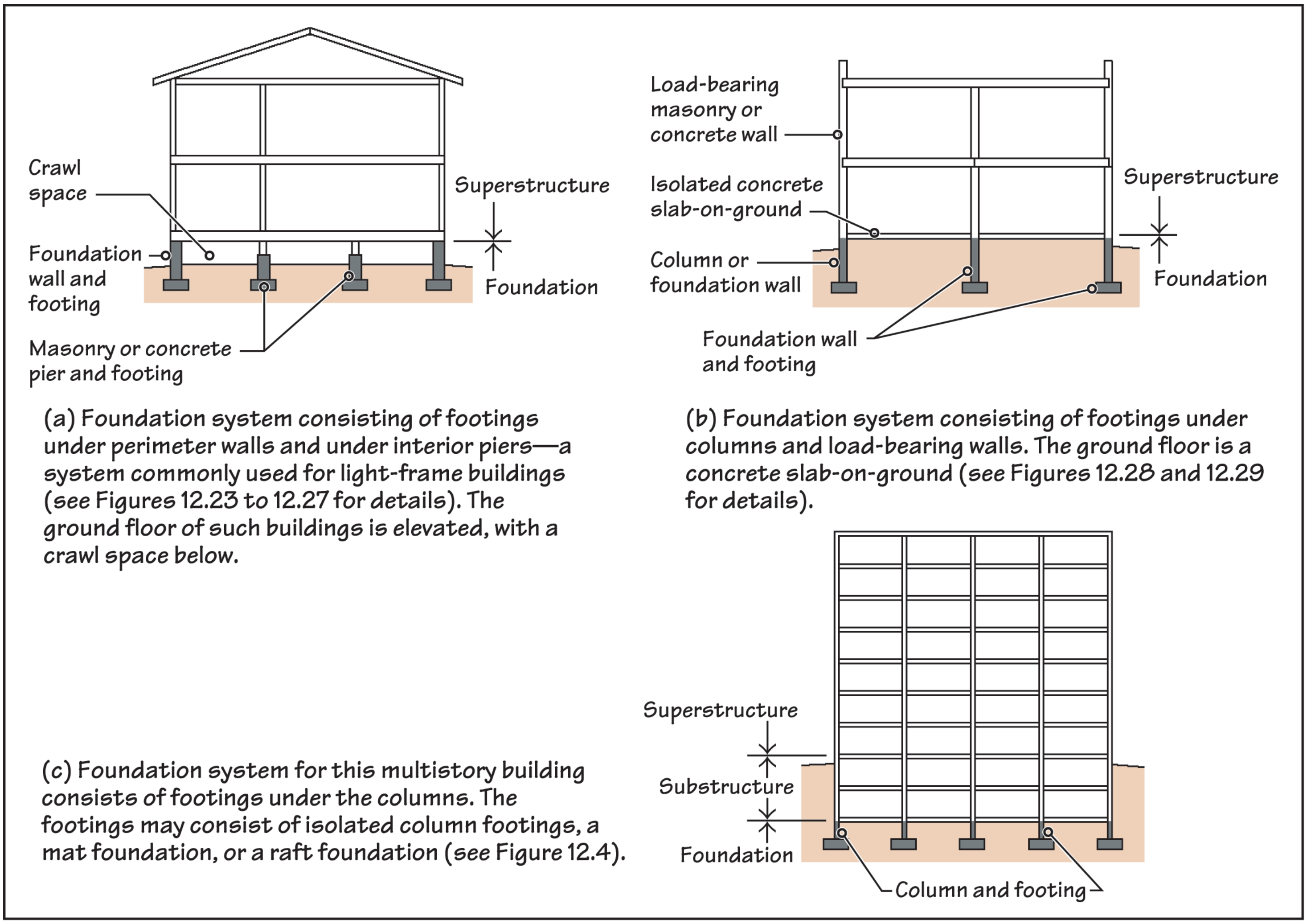
The widened base of a column or wall is called the *footing*. Widening of the base is essential because the strength of the soil supporting the column or wall is generally lower than the strength of the material used for the column or wall. Thus, the primary purpose of a footing is to distribute the superimposed load on a large area of the soil so that the pressure on the soil is less than or equal to the soil's strength (bearing capacity). Most footings are constructed of reinforced concrete, but plain concrete footings may be used for lightly loaded walls. Commonly used foundation systems with footings are as follows:

- Footings under perimeter foundation walls and interior piers (short columns) with an elevated ground floor, Figure 12.2(a).
- Footings under columns and load-bearing walls with a concrete slab-on-ground, Figure 12.2(b).
- Isolated column footings with or without a basement, Figure 12.2(c).

TYPES OF FOOTINGS

As shown in Figure 12.3, footings are of the following types:

- *Continuous wall footings*, also called *strip footings*, are commonly used where the superimposed loads are linear, generally from a load-bearing wall, Figure 12.3(a).
- *Isolated* (independent) *footings* are used where the superimposed load is a point load—for example, from a column, Figure 12.3(b). The bearing capacity required under a column footing is generally higher than that under a wall footing because of the concentrated load on the column. Sometimes, particularly with steel columns, a stepped footing (with a pedestal) is used to save concrete, Figure 12.3(c).
- A *combined footing* is a combination of two isolated column footings. It is used where two or more adjacent columns are closely spaced and heavily loaded. Combining them into one footing reduces the excavation cost and distributes the load over a larger area, Figure 12.3(d). A combined footing is also used where an exterior column must be placed within the property line or adjacent to an existing building, Figure 12.3(e).


Crawl space
Foundation wall and footing
Masonry or concrete pier and footing
Superstructure
Foundation
Load-bearing masonry or concrete wall
Isolated concrete slab-on-ground
Column or foundation wall
Foundation wall and footing
Superstructure
Foundation
Superstructure
Substructure
Foundation
Column and footing

(a) Foundation system consisting of footings under perimeter walls and under interior piers—a system commonly used for light-frame buildings (see Figures 12.23 to 12.27 for details). The ground floor of such buildings is elevated, with a crawl space below.

(b) Foundation system consisting of footings under columns and load-bearing walls. The ground floor is a concrete slab-on-ground (see Figures 12.28 and 12.29 for details).

(c) Foundation system for this multistory building consists of footings under the columns. The footings may consist of isolated column footings, a mat foundation, or a raft foundation (see Figure 12.4).

FIGURE 12.2 Commonly used shallow foundation systems with footings.

Two alternatives to a combined footing are the *strap footing*, Figure 12.3(f) and the *cantilevered footing*, Figure 12.3(g), in which a cantilevered grade beam spans between the two isolated column footings.

MONOLITHIC CONCRETE FOUNDATION UNDER THE BUILDING'S ENTIRE FOOTPRINT

The foundation system consisting of a large monolithic concrete base, generally covering the entire footprint of the building, can be of three types:

- A *slab-on-ground foundation* is the most widely used monolithic foundation system because of its low cost and ease of construction. It is the system of choice for low-rise, light-frame residential or commercial buildings, such as single-family homes, multifamily homes, motels, and professional offices. The slab functions as a foundation system and also as the ground floor of the building, Figure 12.4(a). The slab-on-ground may be a reinforced concrete slab or a posttensioned concrete slab.
- In a *mat foundation*, also called a *mat footing*, all columns and walls of a building bear on one large, thick reinforced concrete slab, Figures 12.4(b) and (c). This foundation is used where the bearing capacity of the soil is low (even deep below the surface) so that independent column footings become so large that only small, unexcavated areas remain between the footings. If the excavation required for isolated footings in a building is more than 50% of the footprint of the building, it is generally more economical to use a mat foundation.
- A mat foundation is also used where the bedrock is so deep that the use of a deep foundation system (drilled piers and piles) is uneconomical. Because of the large thickness

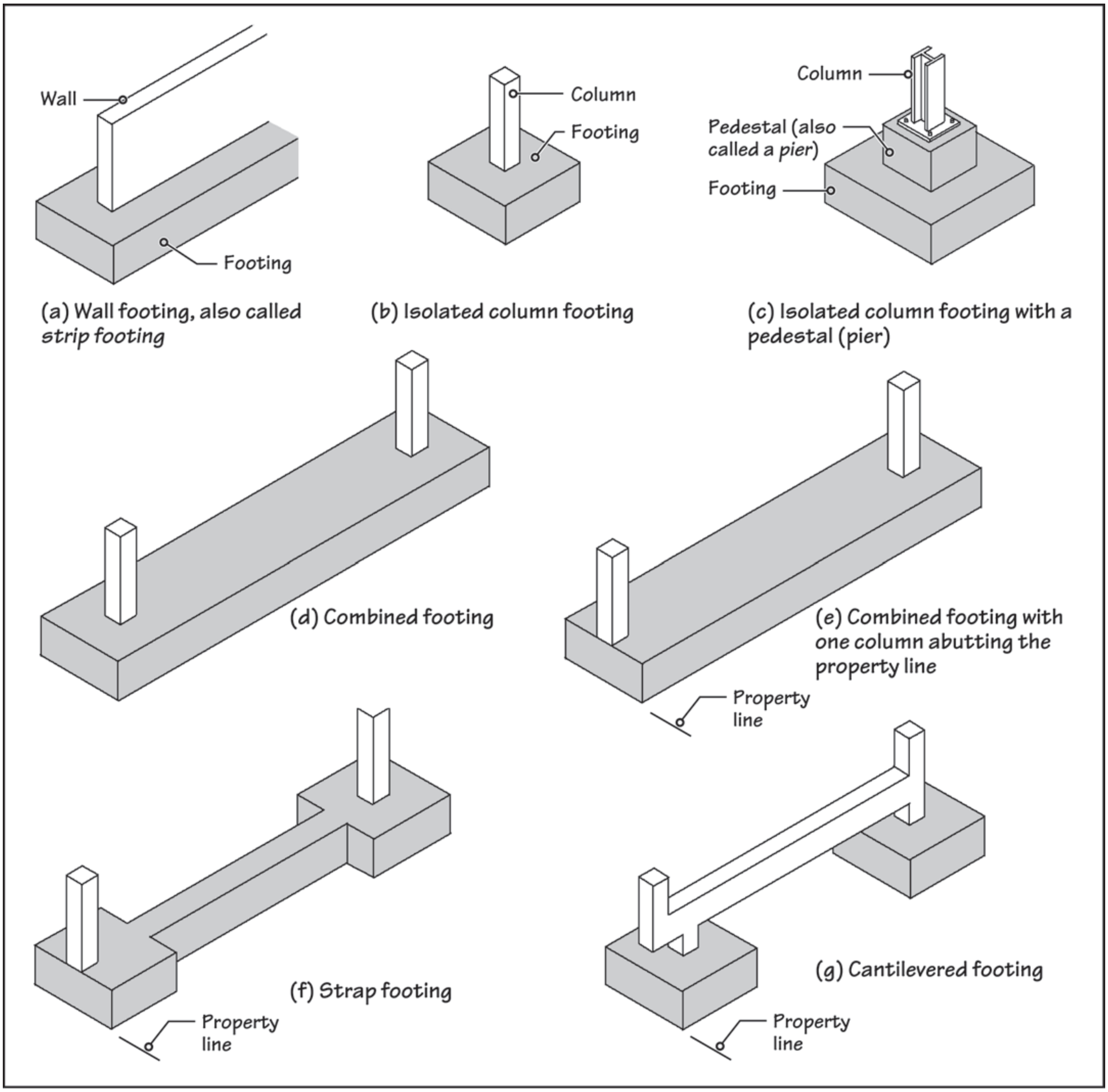

Wall
Footing
(a) Wall footing, also called strip footing
Column
Footing
(b) Isolated column footing
Column
Pedestal (also called a pier)
Footing
(c) Isolated column footing with a pedestal (pier)
(d) Combined footing
(e) Combined footing with one column abutting the property line
Property line
(f) Strap footing
Property line
(g) Cantilevered footing
Property line

FIGURE 12.3 Commonly used footing types.

of a mat foundation, it is sufficiently rigid to distribute loads from individual columns evenly on the underlying soil.

- A *raft*, also called a *floating foundation*, is a type of mat foundation. It consists of a hollow mat formed by a grid of thick reinforced concrete walls between two thick reinforced concrete slabs, Figure 12.4(d). In this case, the weight of the soil excavated from the ground is equal to the weight of the entire building, so that the pressure on the soil is unchanged from the original condition, making the building float on the soil.

12.2 DEEP FOUNDATIONS

Deep foundation systems include piles and drilled piers that are like slender columns buried in the ground. They are prevented from buckling because they are confined by the soil. Piles and drilled piers transfer the load either to bedrock or to soil of high bearing capacity while passing through unsuitable soil conditions.

Piles are generally steel, timber, or concrete elements driven into the ground, except concrete piles, which can also be site-cast in predrilled holes. Site-cast piles are called *drilled piers* or *caissons*. Thus, contiguous bored concrete piles (shown in Figure 11.23) can be called drilled piers. Another term used for drilled piers is *bored* or *drilled piles*.

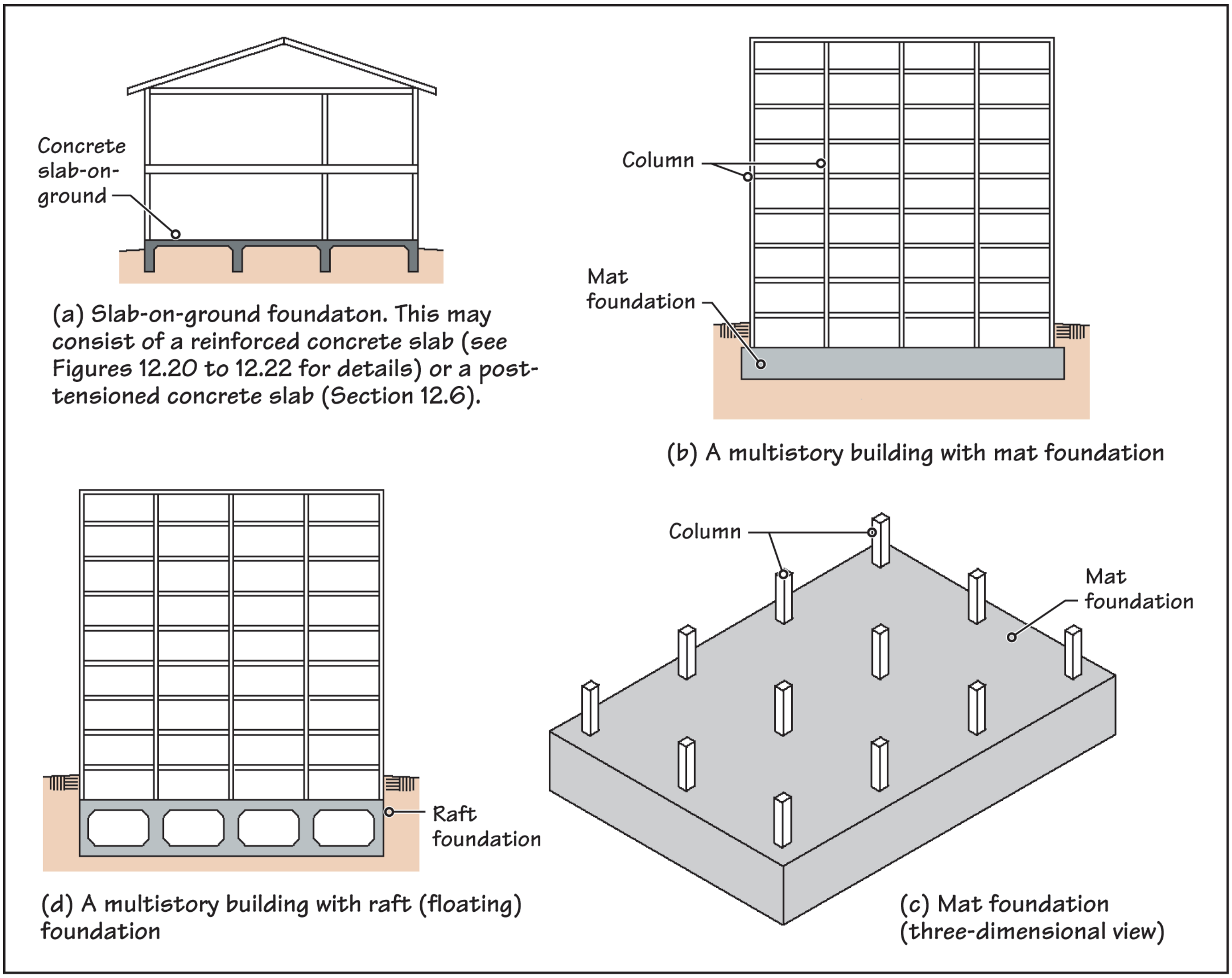

Concrete slab-on-ground
(a) Slab-on-ground foundaton. This may consist of a reinforced concrete slab (see Figures 12.20 to 12.22 for details) or a post-tensioned concrete slab (Section 12.6).
Column
Mat foundation
(b) A multistory building with mat foundation
Column
Mat foundation
Raft foundation
(d) A multistory building with raft (floating) foundation
(c) Mat foundation (three-dimensional view)

FIGURE 12.4 Foundation systems comprising a large, monolithic reinforced concrete base, generally covering the building's entire footprint.

Thus, drilled piers are always of reinforced concrete, while piles (used for foundations, distinct from sheet piles used for excavation support) may consist of reinforced concrete, steel, or timber.

As previously stated, deep foundations are used where shallow foundations cannot be used because the pressure imposed by the structural elements is too large (e.g., under the columns of a tall building) for the soil's bearing capacity at shallow depths, Figure 12.5(a).

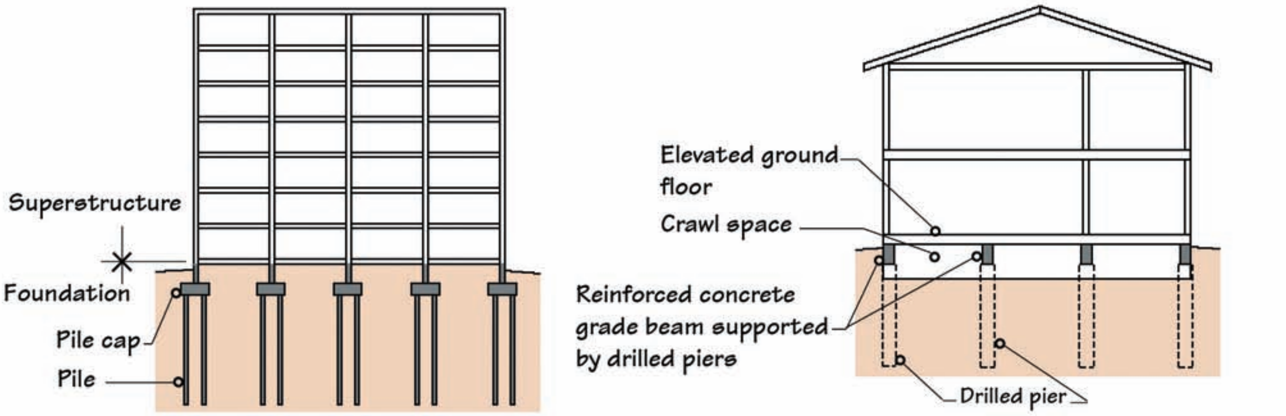
Deep foundations are also used in low-rise, lightly loaded buildings in situations where the soil near the surface is unstable. Figure 12.5(b) shows the foundation system of a low-rise building consisting of reinforced concrete grade beams supported on drilled piers—commonly used in unstable soil conditions. The ground floor of this building is supported on grade beams with a crawl space under the floor, similar to that of Figure 12.2(a).

Figure 12.5(c) shows a foundation system that is an alternative to that of Figure 12.5(b), where the ground floor consists of a concrete slab supported on grade beams that bear on drilled piers. Figure 12.5(d) shows another alternative in which the ground floor slab is supported on enlarged concrete caps that bear on drilled piers.

Because the settlement of deep foundation systems is relatively small, deep foundations are also used in buildings that house items or instruments sensitive to even small amounts of settlement, which is likely to occur in shallow foundations.

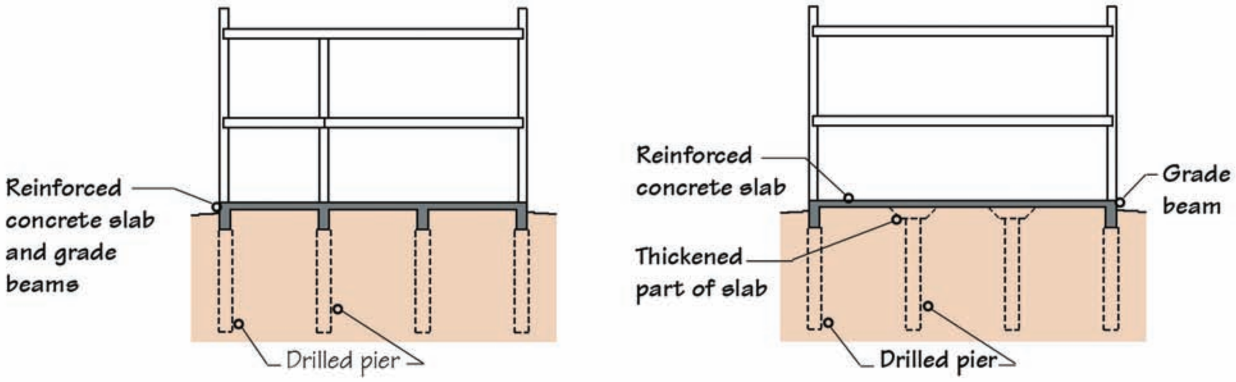
12.3 PILES AS DEEP FOUNDATIONS

As previously mentioned, steel, precast concrete, and wood are common pile materials. The material selected depends on availability, cost, below-grade environment, type of soil, the load to be supported, and the equipment required to drive the piles. Steel and concrete piles are generally used under heavier loads. Wood piles are limited in their load-bearing


Superstructure
Foundation
Pile cap
Pile
Elevated ground floor
Crawl space
Reinforced concrete grade beam supported by drilled piers
Drilled pier

(a) Piles and pile caps under columns as foundation system for a multistory building. Piles may be replaced by drilled piers. Drilled piers are used individually and do not need caps.

(b) Reinforced concrete grade beams supported on drilled piers—a foundation system commonly used for light frame buildings where the upper soil strata is of low bearing capacity or expansive (see Figures 12.30 to 12.33 for details).


Reinforced concrete slab and grade beams
Drilled pier
Reinforced concrete slab
Grade beam
Thickened part of slab
Drilled pier

(c) Reinforced concrete grade beams and ground floor slab supported on drilled piers—a foundation system commonly used for buildings where the upper soil strata is of low bearing capacity or expansive (see Figures 12.34 and 12.35).

(d) Reinforced concrete slab supported directly on drilled piers. The slab is thickened in the vicinity of piers. The system is an alternative to that of Figure 12.5(c). For details, see Figure 12.36.

FIGURE 12.5 Commonly used deep foundation systems.

capacity because of the nature of the material and the limitations on the cross-sectional area of tree trunks.

Steel piles may be H-shaped or hollow pipes. Hollow steel piles are filled with concrete after being driven. Steel piles are covered with protective coatings if used in corrosive environments. Concrete piles are made of precast concrete and are generally solid. They are subject to attack by the sulfur present in some soils, requiring the use of sulfate-resistant Portland cement (Chapter 21). Concrete piles can be provided with a steel tip extension for easier penetration. Wood piles are treated with creosote or chromated copper arsenate (CCA) as a preservative. (For a discussion of CCA, see Section 13.15.)

Piles support loads through two mechanisms. Piles that support loads primarily through friction created between the surface of the pile and the soil are called *friction piles*, Figure 12.6(a). They are generally tapered to a narrow cross section at the bottom to facilitate driving. Piles that transfer most of the load to the bottom stratum, with very little through friction, are called *tip-bearing* or *end-bearing piles*, Figure 12.6(b). For piles driven in weak soils, the end reaction from tip bearing may be ignored.

Because they are driven, piles are smaller in cross section than drilled piers, and the load capacity of an individual pile is also small. Piles are, therefore, used in clusters of three or more at 2 ft to 3 ft on center and support a reinforced concrete cap called a *pile cap*. A pile cap functions like an isolated column footing or a continuous strip footing under a wall, Figure 12.7. Two or more columns can be placed on a large pile cap.

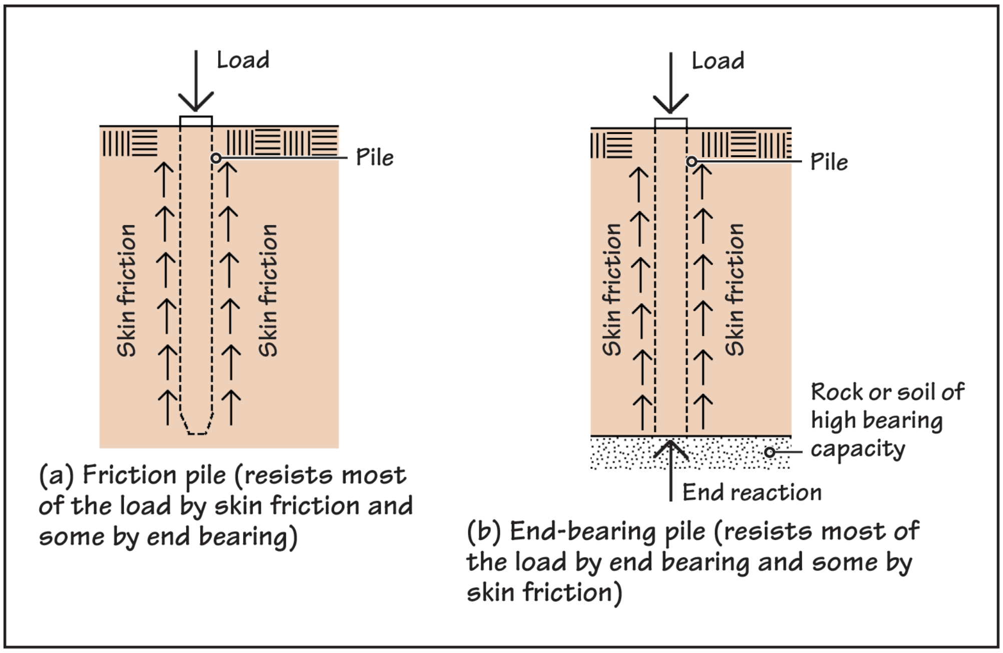

Load
Pile
Skin friction
Skin friction
(a) Friction pile (resists most of the load by skin friction and some by end bearing)
Load
Pile
Skin friction
Skin friction
Rock or soil of high bearing capacity
End reaction
(b) End-bearing pile (resists most of the load by end bearing and some by skin friction)

FIGURE 12.6 Friction piles and end-bearing piles.

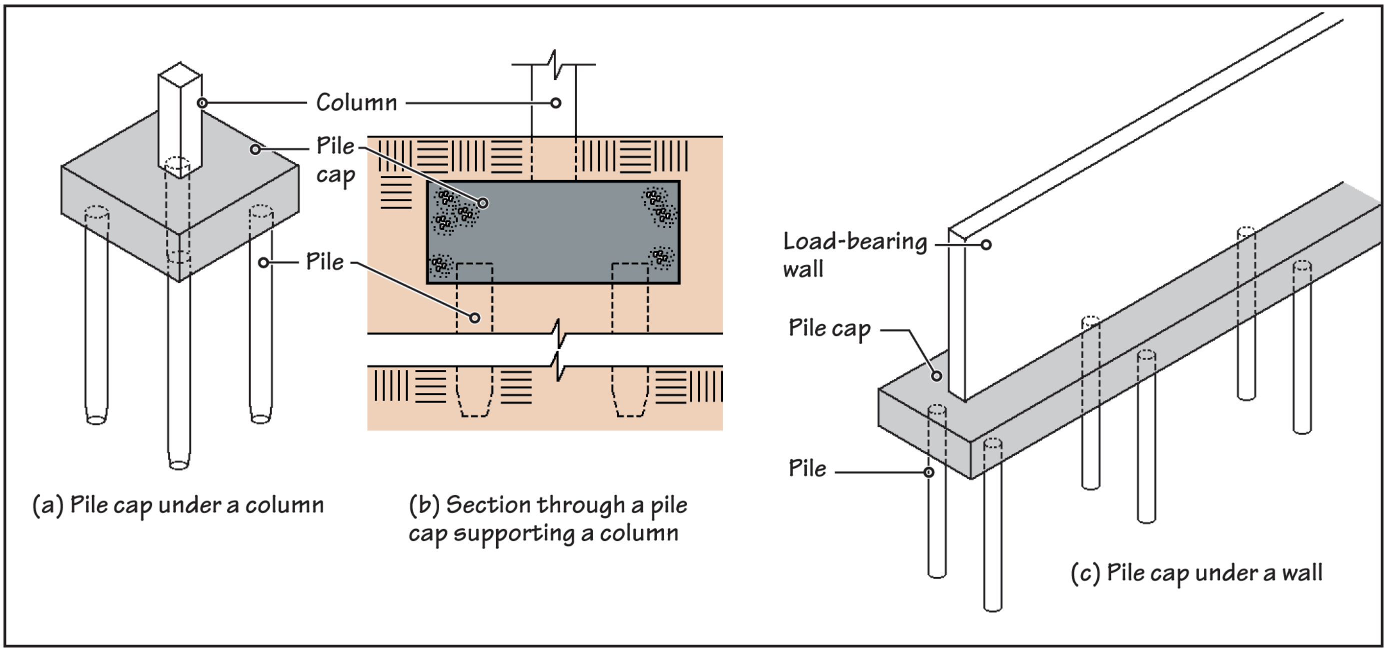

Column
Pile cap
Pile
(a) Pile cap under a column
(b) Section through a pile cap supporting a column
Load-bearing wall
Pile cap
Pile
(c) Pile cap under a wall

FIGURE 12.7 Reinforced concrete pile caps over a cluster of piles.

DRIVING OF PILES

Although pile-driving machines (Figure 12.8) come in different types, depending on the type of soil and the pile material, they basically consist of a heavy weight placed between guides so that it can move up and down in a straight line. The driving force comes from the repeated hammering action as the weight is dropped on the pile head, raised, and dropped again, using diesel, hydraulics, or compressed air for the operation.

12.4 DRILLED PIERS AS DEEP FOUNDATIONS

Drilled piers are often used individually (as opposed to a cluster of piles) because they can be made almost as large as required. The drilled pier diameter generally varies between 18 and 36 in. Larger-diameter piers (6 ft in diameter or larger) are used for bridges or high-rise structures. Another reason for using individual piers is that their vertical alignment is almost assured. (Because piles are driven, alignment is uncertain. Therefore, an individual pile is seldom used.)

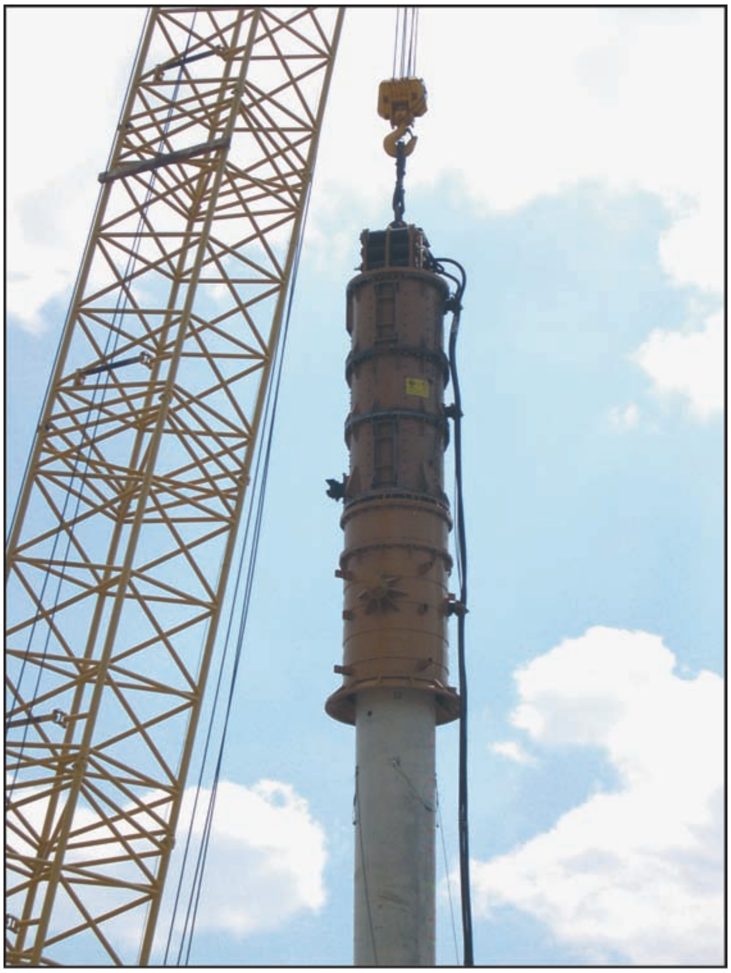


FIGURE 12.8 A round concrete pile being driven by a hydraulic impact hammer. (Photo courtesy of Pile Driving Contractors Association [PDCA], Orange Park, Florida)

Like piles, piers may also be designed as *friction piers* or *end-bearing piers* or both. Drilled piers may either have a straight shaft or be belled at the bottom, Figures 12.9(a) and (b). A belled pier has a straight shaft with an enlarged bottom that bears on a high-capacity soil. Because of the enlarged bottom, its load-carrying capacity is larger than that of a straight-shaft pier. However, belled piers are not practical in noncohesive soils because of soil caving.

Piers that bear on rock may be socketed (i.e., penetrate into rock, referred to as *rock sockets*), Figure 12.9(c). Socketed piers are generally used where the upper stratum consists of soft soil that is unable to provide significant skin friction. The load-carrying capacity of such piers is developed from skin friction in rock in addition to end bearing.

UPLIFT PRESSURE ON DRILLED PIERS IN EXPANSIVE SOILS

Piers that are used in expansive soils are subjected to uplift pressure caused by soil expansion. In such soils, the uplift pressure on the pier from the upper, expansive zone of the soil (referred to as the *active zone*) must be countered by skin friction from the lower, stable (inactive) zone of the soil, Figure 12.10. Where the (lower) stable zone is not sufficiently deep, the pier may need to be socketed in the rock to provide the necessary anchorage against uplift. A belled pier may also be used for the same reason.

CONSTRUCTION OF DRILLED PIERS

Piers are generally constructed by first drilling a hole of predetermined diameter into the soil (and later into the rock for a socketed pier). This is accomplished by a truck-mounted rig furnished with a drilling auger. An auger consists of a continuous blade formed into an open helix (drill). Different augers are used for cutting into soil and rock. Soil augers are simple blade-type augers, Figure 12.11. Augers used for cutting into rock or hard soil are provided with carbide-tipped teeth.

As the auger rotates, the soil or rock cut by the auger collects in the spaces between the auger helix. When the space gets filled, the auger is brought up and moved away from the hole. The cut material is then spun off (the auger drill is rotated vigorously in the opposite direction), and the auger is lowered again into the hole for additional cutting.

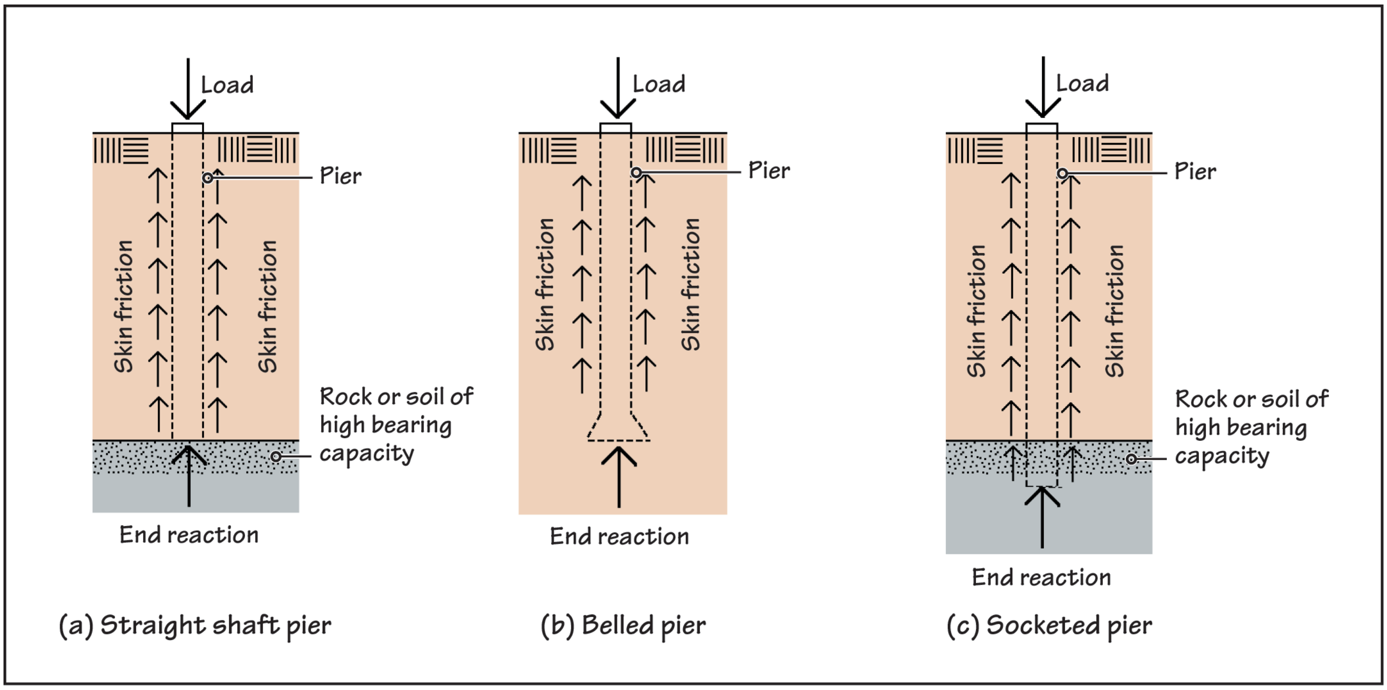

Load
Pier
Skin friction
Skin friction
Rock or soil of high bearing capacity
End reaction
(a) Straight shaft pier
Load
Pier
Skin friction
Skin friction
End reaction
(b) Belled pier
Load
Pier
Skin friction
Skin friction
Rock or soil of high bearing capacity
End reaction
(c) Socketed pier

FIGURE 12.9 Types of drilled (bored) piers.

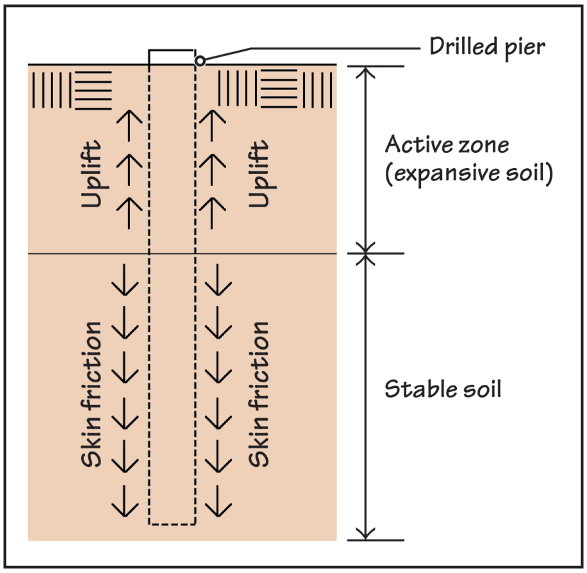


FIGURE 12.10 An expansive soil creates uplift on a drilled pier as it swells. This uplift force must be counteracted by skin friction and (or) end anchorage, particularly if the dead load on the pier is small.

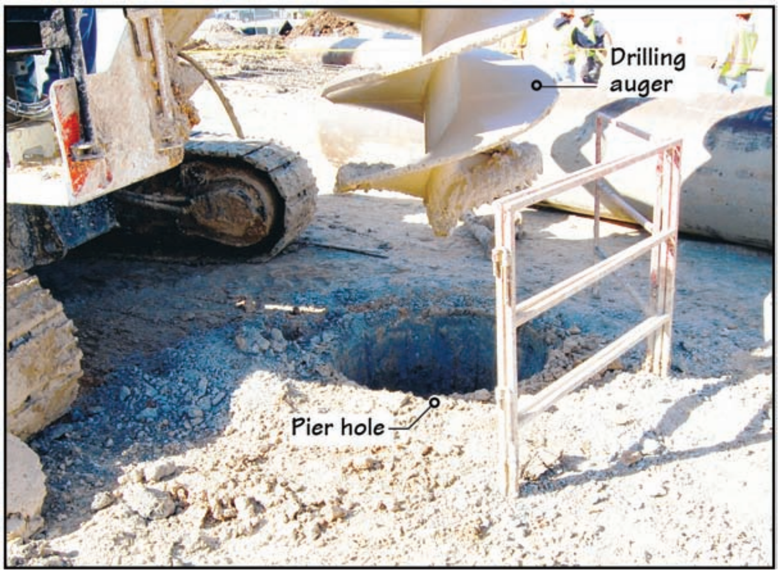


FIGURE 12.11 A typical auger for drilling hole in the soil.

After the hole has been drilled to the required depth, a steel reinforcement cage is lowered into the hole, Figure 12.12, and concrete is placed in the hole. Placement of concrete is generally done using a tremmie, which is a steel pipe topped by a funnel, Figure 12.13. The tremmie takes the concrete close to its intended location and prevents separation of concrete particles, which would occur if the concrete were dropped from a distance. The tremmie is removed after all concrete has been placed. Various holes provided in tremmie shaft ensure concrete's proper placement.

If the drilled hole is deep, and (or) if there is a possibility of the soil caving in, a temporary steel casing is inserted in the hole as the drilling advances, Figure 12.14. A steel casing is a hollow tube whose diameter is slightly smaller than that of the drilled hole. The casing is extracted after placing concrete in pier hole.

Steel casing is also used in water-bearing soils to prevent the entry of water into the hole. The bottom of the casing is sealed by spinning it into the rock (rock does not contain water) while applying a downward vertical force, Figure 12.15. After sealing of the hole, the water is removed, reinforcement is lowered, and the concreting operation is begun. The small amount of water left in the hole floats on top of the concrete because it is lighter than concrete. This water is removed after the entire hole has been concreted. The casing is now gradually removed from the hole while the concrete is still green. Some additional concreting is required during this operation to fill the void created by the removal of casing.

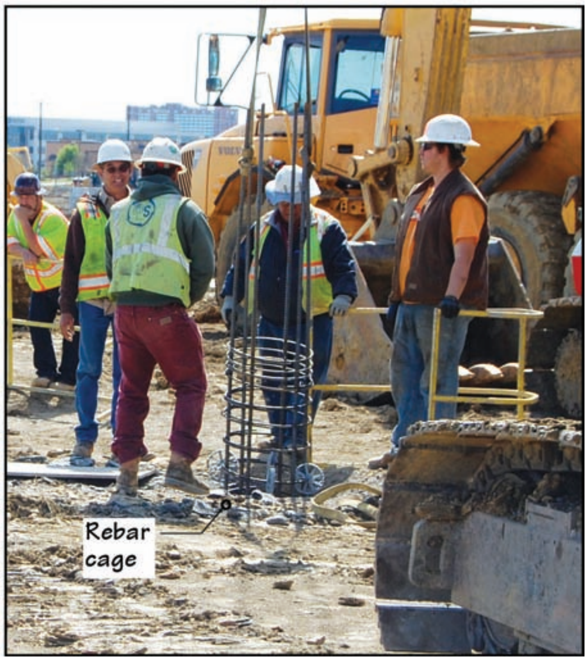


FIGURE 12.12 Rebar cage being lowered into pier hole with the help of a fork lift, not seen in photograph.

DRILLED PIER TERMINATION

Where a pier is used to support another concrete member (a grade beam or concrete column), steel reinforcing dowels that extend beyond the top of the pier are placed in the member before concreting is completed, Figures 12.16(a) and (b). For a pier that supports a steel column, the pier top is provided with steel anchor bolts, Figure 12.16(c).

PILES VERSUS DRILLED PIERS

Piles and piers have their own unique applications. Piles are ideally suited for marine and coastal sites, where drilled piers are not suitable because of the presence of water, a high water table, or the presence of a sandy soil with cave-in potential. As the pile is driven, an assessment of the soil's bearing capacity is obtained from the blow count and the resulting pile penetration. Piles can be used immediately, with no wait time for the concrete to cure. However, pile driving is noisy and requires heavier equipment. It also disturbs the surrounding area with vibrations caused by the driving operations.

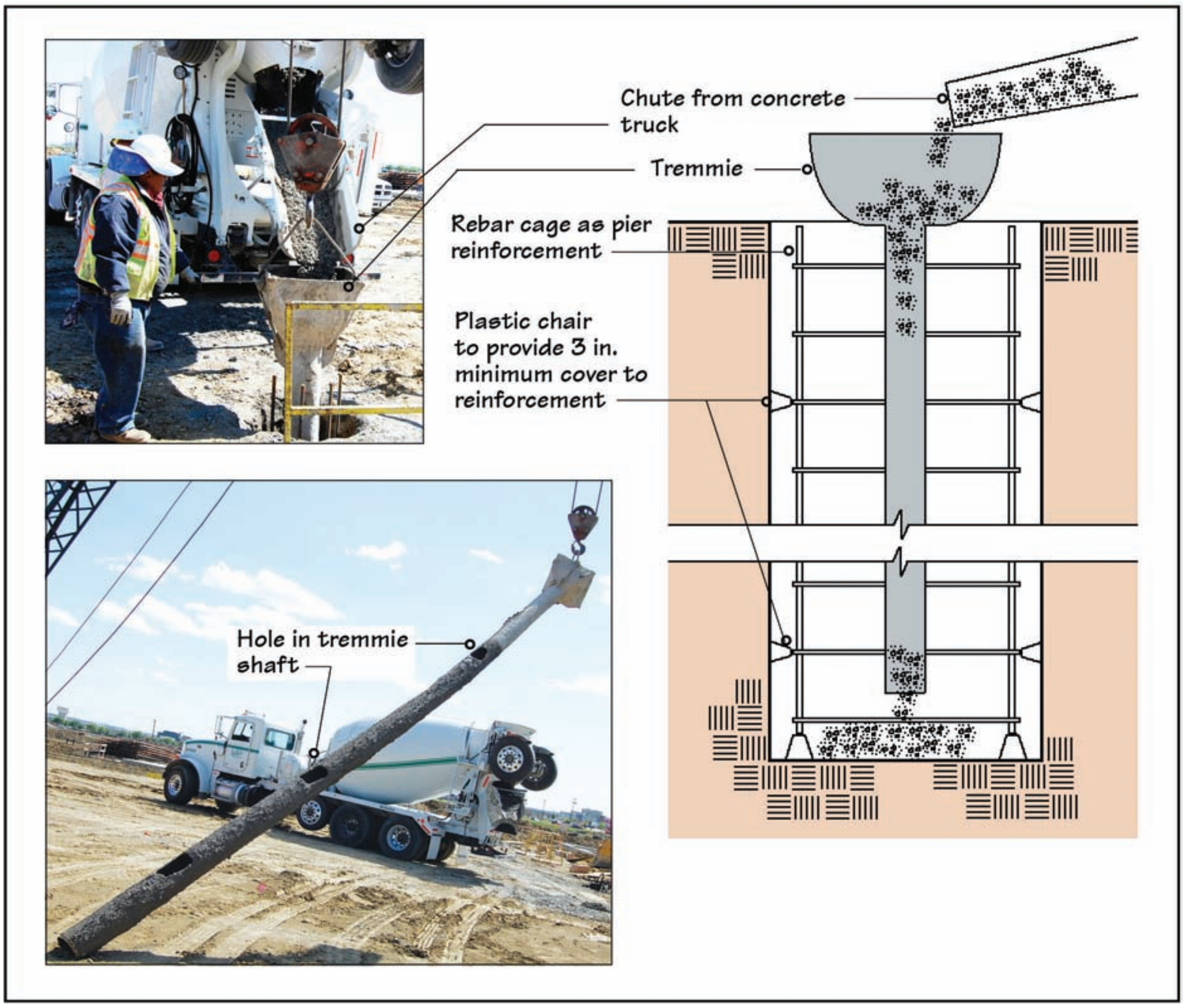

Chute from concrete truck
Tremmie
Rebar cage as pier reinforcement
Plastic chair to provide 3 in. minimum cover to reinforcement
Hole in tremmie shaft

FIGURE 12.13 The use of a tremmie for placing concrete into a pier hole.

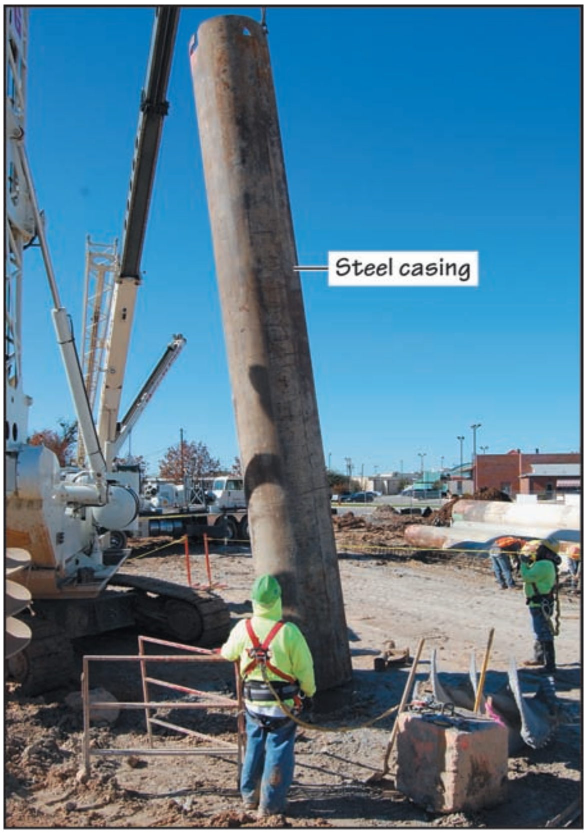


FIGURE 12.14 A steel casing being lowered into a pier hole.

Piers are particularly suited for urban locations where vibrations and noise from pile driving are unacceptable. They can also support a much larger load than a pile and, unlike piles, do not require capping.

The technology required for piers is less complex; hence, drilled piers are generally more economical than driven piles. For this reason, piers are popular for foundation systems for low-rise buildings in expansive (clay) soils.

12.5 FOUNDATION SETTLEMENT

All foundation systems require a determination of the bearing pressure created by the loads on the underlying stratum (soil or rock). This bearing pressure must be less than the stratum's allowable bearing capacity (see Section 11.4). In addition to having an adequate bearing capacity, foundations must resist settlement. This is generally of greater concern for shallow foundations because they bear on a more compressible stratum than deep foundations.

IMMEDIATE AND CONSOLIDATION SETTLEMENT

Settlement occurs as the soil compresses under the loads. The greater the soil's compressibility, the greater is the settlement. In coarse-grained soils, settlement is immediate; that is, it occurs as the load is applied. Therefore, most of the settlement in coarse-grained soils occurs during the construction of the building. In fine-grained (particularly clayey) soils, part of the settlement is immediate, and the remainder (called *consolidation settlement*) occurs over a period of several months or years. Consolidation settlement occurs when the water held between clay particles is squeezed out by the load, and the soil consolidates and shifts.

UNIFORM AND DIFFERENTIAL SETTLEMENT

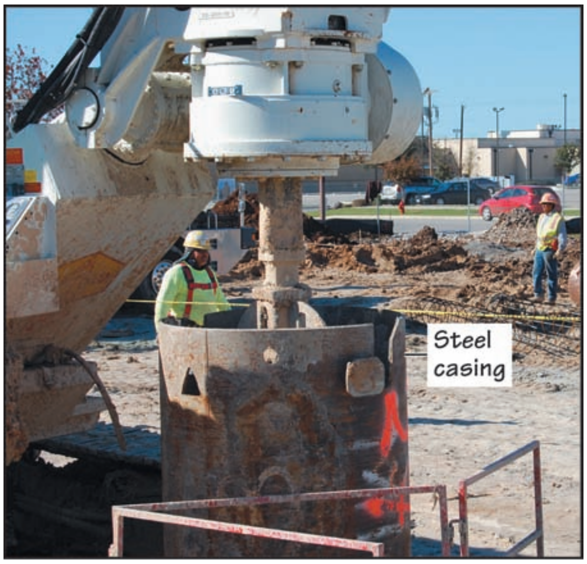


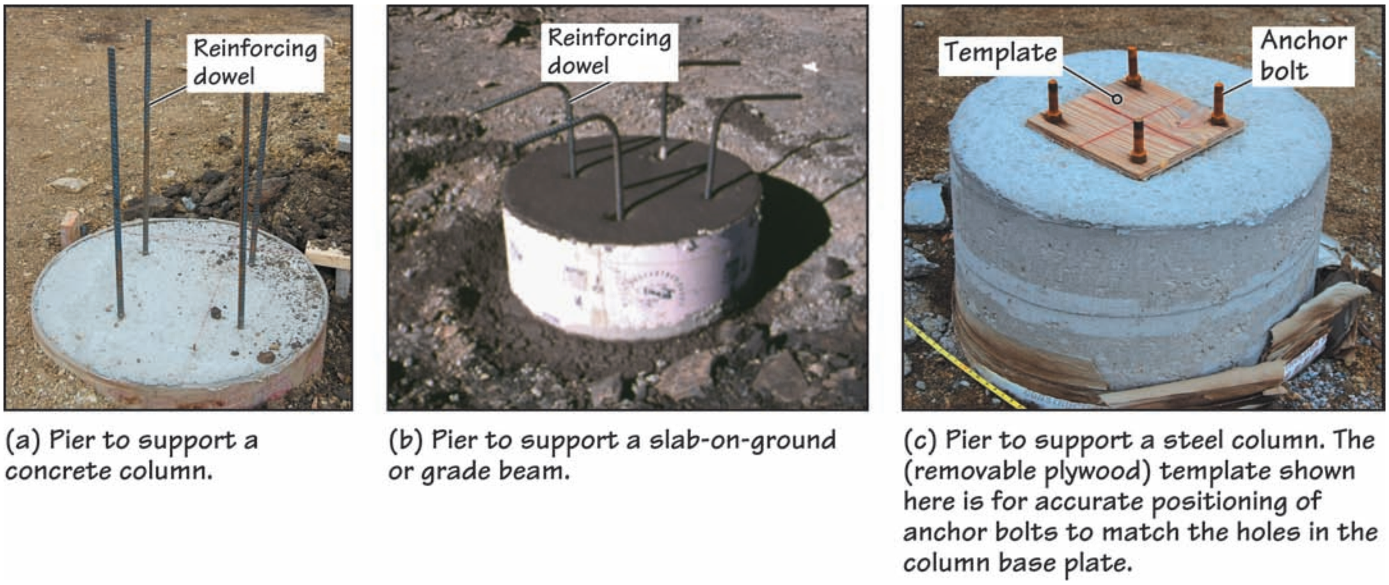
FIGURE 12.15 Steel casing being rotated to push it into hard soil (or rock) to seal its bottom against the entry of water.

Settlement may be uniform over the entire structure or nonuniform (referred to as *differential settlement*). In uniform settlement, the entire structure settles by the same amount. In the case of excessive settlement, the ground floor of a building may sink to below the finished ground level, Figure 12.17(b).

One of the most frequently cited examples of the sinking of building foundations comes from Mexico City, which is sited on a soft soil. The increase in the city's population has led to the excessive use of underground water, resulting in the gradual lowering of the ground surface. The ground floor of the famous Palacio de Bellas Artes (Palace of Fine Arts) in Mexico City (designed by architect Federico Mariscal) has sunk by about 14 ft since it was completed in 1934. Fortunately, the settlement has been uniform, so the resulting problems were easily solved.

Differential settlement is more serious. It leads to the deformation of the structural frame, imposing stresses on the structure for which it has not been designed and possible structural failure, Figure 12.17(c). Building codes specify the maximum permissible amount of differential settlement of footings.

Properly designed and constructed foundation systems with a monolithic base (mat or raft foundations) have negligible differential settlement due to their rigidity. Differential settlement is an important design consideration in foundation systems consisting of multiple footings because of the local variation in soil's compressibility, uneven compaction, and uneven bearing pressure induced on the soil by the superimposed loads. Therefore, footing dimensions are determined not merely on the bearing capacity of the soil but also on footing settlement—to ensure that all footings in the building have approximately the same amount of settlement.

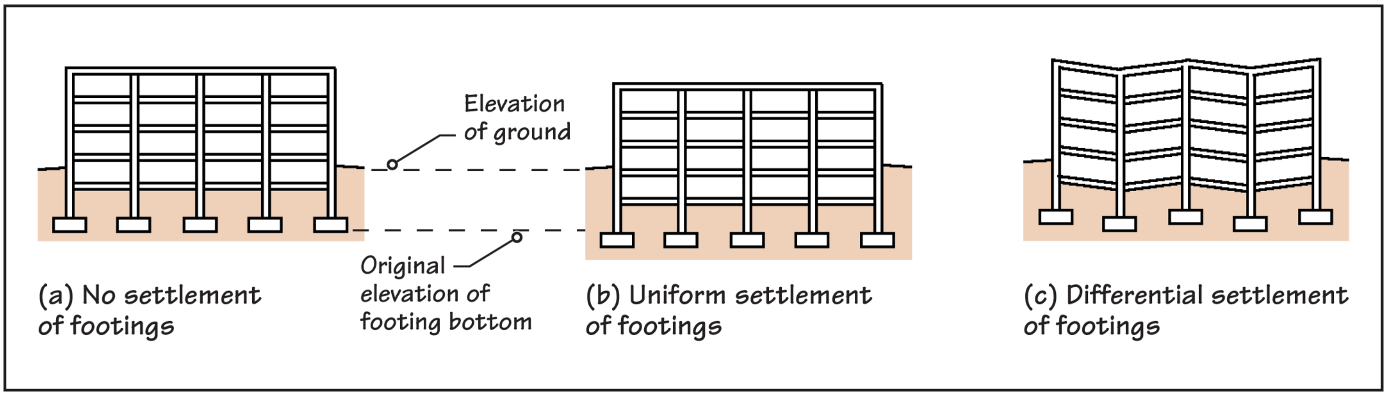


(a) Pier to support a concrete column.

(b) Pier to support a slab-on-ground or grade beam.

(c) Pier to support a steel column. The (removable plywood) template shown here is for accurate positioning of anchor bolts to match the holes in the column base plate.

FIGURE 12.16 Steel anchor bolts or reinforcing dowels are provided in the pier for anchorage to the structural member to be supported by the pier.



(a) No settlement of footings

(b) Uniform settlement of footings

(c) Differential settlement of footings

FIGURE 12.17 Uniform and differential settlement of footings.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. A raft foundation is a shallow foundation system.
- **a.** True
- **b.** False

2. Which of the following foundation systems does not extend, generally uninterrupted, for the entire footprint of the building?
- **a.** Slab-on-grade foundation
- **b.** Mat foundation
- **c.** Raft foundation
- **d.** Pier or pile foundation

3. A strip footing is generally used under a
- **a.** column.
- **b.** wall.
- **c.** drilled pier.
- **d.** pile.
- **e.** all of the above.

4. A strap footing is generally used where
- **a.** the soil is expansive.
- **b.** the soil has low bearing capacity.
- **c.** the columns in the buildings are closely spaced.
- **d.** the columns in the building abut the property line.
- **e.** none of the above.

5. A deep foundation system consists of a
- **a.** slab-on-ground foundation.
- **b.** mat foundation.
- **c.** raft foundation.
- **d.** pier or pile foundation.
- **e.** all of the above.

6. Which of the following foundation items must be integrated under a concrete cap?
- **a.** Isolated column footings
- **b.** Wall footings
- **c.** Driven piles
- **d.** Drilled piers
- **e.** All of the above

7. Drilled piers used as foundation elements consist of
- **a.** cast-in-place reinforced concrete.
- **b.** cast-in-place unreinforced concrete.
- **c.** precast concrete.
- **d.** structural steel.
- **e.** wood.

8. Which of the following foundation system has large voids?
- **a.** Concrete slab-on-ground
- **b.** Mat foundation
- **c.** Raft foundation
- **d.** Strip footing
- **e.** None of the above

9. Pile foundations are commonly used in coastal areas.
- **a.** True
- **b.** False

10. Drilled piers transfer building loads mainly by end bearing, while piles do so by both end bearing and skin friction.
- **a.** True
- **b.** False

11. In expansive soils, drilled piers are subjected to
- **a.** a downward force in the expansive region of the soil, which generally occurs well below the ground surface.
- **b.** an uplift force in the expansive region of the soil, which generally occurs well below the ground surface.
- **c.** an uplift force in the expansive region of the soil, which generally occurs in the upper soil layer.
- **d.** any one of the above, depending on the local geology.
- **e.** none of the above.

12. The augers used for boring pier holes generally use
- **a.** a hammering operation.
- **b.** a vibratory operation followed by a hammering operation.
- **c.** a rotary operation with a helix-type blade cutter.
- **d.** a rotary operation followed by a hammering operation.
- **e.** none of the above.

13. A tremmie is used during the drilling of a pier to
- **a.** prevent the caving in of the soil.
- **b.** bring the cut soil out of the hole.
- **c.** bring up the groundwater that collects at the bottom of the pier.
- **d.** seal the pier hole against percolation of water.
- **e.** none of the above.

14. Where a tremmie is used in a pier, casing is unnecessary.
- **a.** True
- **b.** False

15. In a deep foundation system, foundation settlement is generally larger than in a shallow foundation system.
- **a.** True
- **b.** False

16. Settlement of foundations causes stresses in the structural frame of the building when the settlement is
- **a.** caused by live loads.
- **b.** caused by dead loads.
- **c.** caused by lateral loads.
- **d.** large and uniform over the entire foundation area.
- **e.** nonuniform over the foundation area.

12.6 FOUNDATION DRAINAGE

Most building assemblies are adversely impacted by water. Water accelerates wood decay and promotes the growth of mold and fungi. Specifically with respect to foundations, water in the soil increases lateral pressure on basement and crawl space walls, corrodes reinforcement in concrete and masonry, and causes heaving of soil during freezing weather. Additionally, excess water can cause flooding of basements and crawl spaces and provide a breeding ground for mosquitoes. Clayey soils are particularly vulnerable to excess water because of their swell-shrink characteristic.

Two types of water can affect a building: (a) *surface water* from rain and snow melt and (b) *subsurface water* (also called *groundwater*). Surface water control is obtained by sloping the finished ground away from the building. It is important that sufficient slope is provided to divert water quickly away from the building so as to reduce its potential to seep into the ground and add to the groundwater. A 4% slope ($\frac{1}{2}$ in. per foot), provided over the first 10 ft from the building, is generally considered adequate.

CONTROL OF GROUNDWATER—FRENCH DRAIN

While the control of surface water is important in all buildings, the control of groundwater is generally required only in buildings with a basement or crawl space—to reduce water pressure on basement and crawl space walls. This is achieved by installing a drainage system all around the foundation. The drainage system consists of a perforated drain pipe placed in a narrow trench and surrounded with a drainage medium consisting of clean (preferably washed), crushed stone or gravel. A filter fabric, made of a synthetic material, encapsulates the drainage medium. The filter fabric captures fine soil particles and prevents them from clogging the voids in the drainage medium and pipe perforations. A number of terms, such as *French drain*, *trench drain*, and *footing drain*, are used for this drainage system.

The pipe, generally 4 to 6 in. in diameter, made of polyvinyl chloride (PVC) or corrugated polyethylene, is perforated on one edge. The perforated edge is placed face down to attract the lowest level of water into the pipe. The pipe must terminate in a storm water drain or in daylight. Alternatively, the pipe may terminate in a sump pit, from where a self-actuated pump lifts the water into a storm drain.

It is important that the drainage system be installed a little above the bottom of the foundation. If installed below the foundation, it may tend to wash away the soil below the foundation. The details of foundation systems given in Sections 12.7 and 12.8 illustrate the concept of foundation drainage.

12.7 DETAILS OF FOUNDATION SYSTEMS ON STABLE SOILS

Some of the commonly used foundation systems for low-rise buildings on stable soils are

- Reinforced concrete slab-on-ground foundation
- Exterior foundation walls, interior piers (short columns), and an elevated ground floor
- Wall and column footings and ground floor comprising a reinforced concrete slab

REINFORCED CONCRETE SLAB-ON-GROUND FOUNDATION

As conceptually diagramed in Figure 12.4(a), a concrete slab-on-ground foundation functions as the ground floor of the building and also as the foundation system for the structural elements of the building. It is easily constructed because it requires little excavation. Excavated trenches function as formwork for concrete work, making it extremely cost effective for low-rise, lightly loaded buildings. Its limitation is that it can only be used in warm climates where the frost depth is small (see Section 11.4 for a discussion of frost depth).

The thickness of the slab is primarily a function of the loads on the slab and the type of soil. A fairly stable soil with low swell-shrink potential (such as a sandy soil) provides a stratum of uniform strength. Over such a stratum, a 5-in.-thick slab with nominal reinforcement, with the perimeter and intermediate beams under load-bearing walls, is adequate.

If the soil has some swell-shrink material that is susceptible to changes in moisture content, the slab needs to be designed as a raft so that it has the required stiffness to float on the soil (move up and down as one thick plate with minimal bending and minor cracking). This requires a thicker slab and a greater amount of reinforcement. In some cases, the slab thickness required may be so great that it is more economical to provide a ribbed slab (also called a *waffle slab*) in place of a slab of constant thickness.

In other words, a ribbed slab can be structurally as strong and stiff as a slab of constant thickness but uses a smaller amount of concrete and steel. A ribbed slab derives its strength and stiffness from its geometry, which comprises a slab intercepted by intermediate beams in both directions, spaced 8 ft to 10 ft apart, in addition to perimeter beams.

Figure 12.18 shows the excavation for a ribbed concrete slab-on-ground. This figure further highlights the ease with which a ribbed slab-on-ground foundation can be constructed. The construction of a uniformly thick slab-on-ground foundation is even simpler.

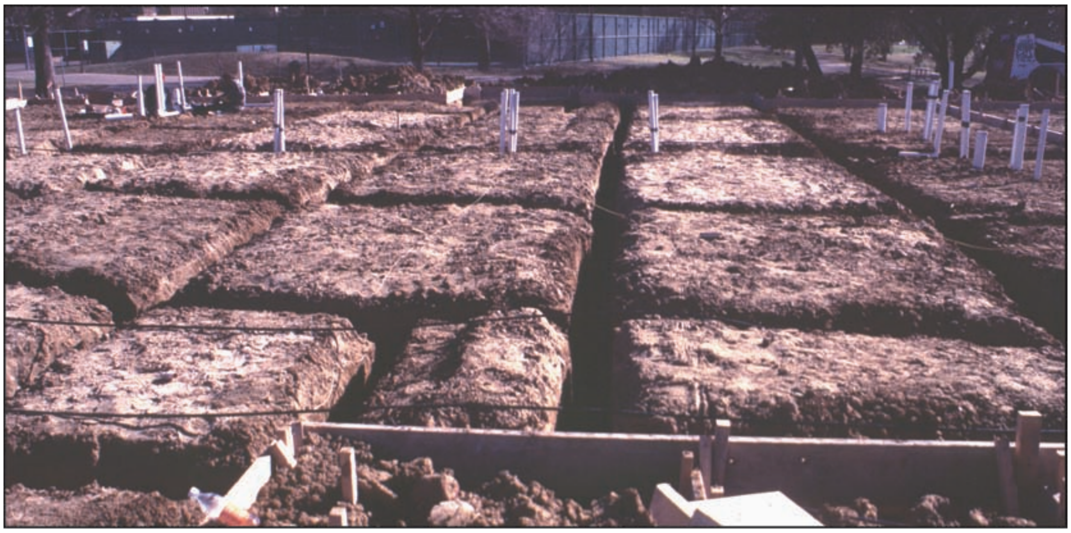


FIGURE 12.18 Excavation for a typical reinforced concrete slab-on-ground foundation showing the network of trenches in both directions. The trenches serve as formwork for concrete beams.

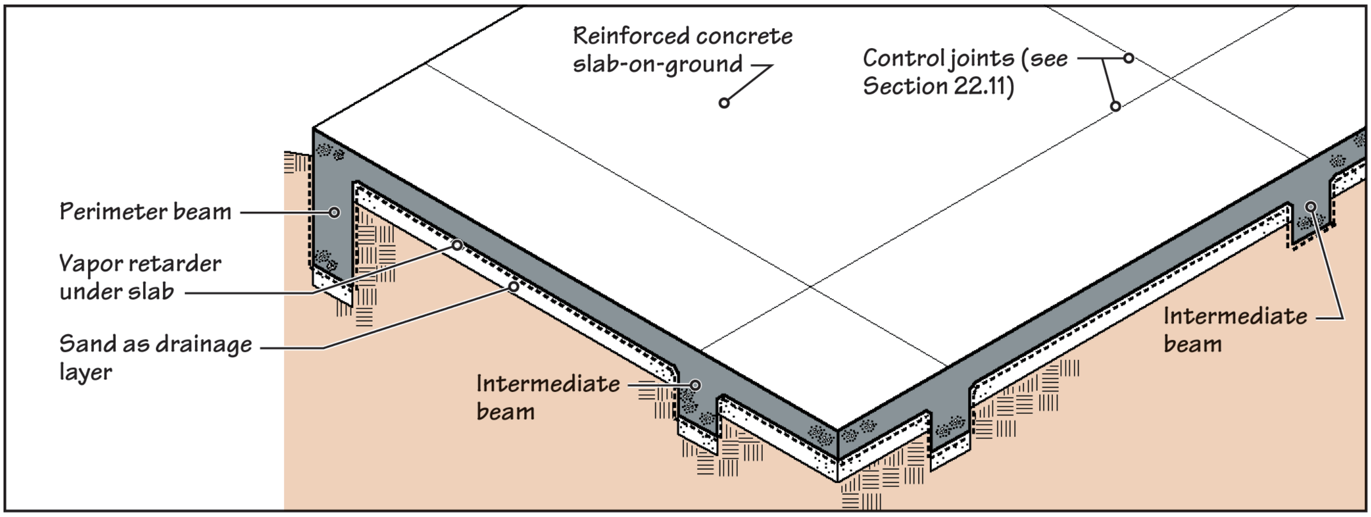

Reinforced concrete slab-on-ground
Control joints (see Section 22.11)
Perimeter beam
Vapor retarder under slab
Sand as drainage layer
Intermediate beam
Intermediate beam

FIGURE 12.19 A typical reinforced concrete slab-on-ground foundation used as a foundation system for low-rise light-frame buildings. The slab is generally a ribbed slab, that is, a slab stiffened with perimeter and intermediate beams in both directions.

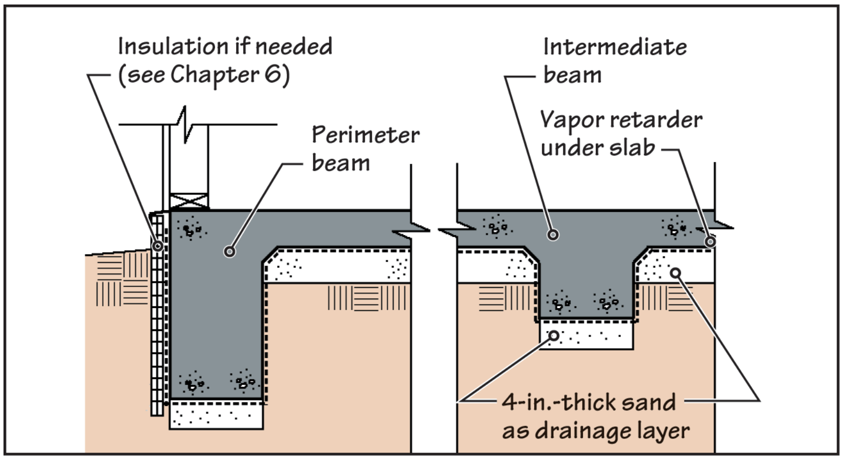

Insulation if needed (see Chapter 6)
Perimeter beam
Intermediate beam
Vapor retarder under slab
4-in.-thick sand as drainage layer

FIGURE 12.20 Part section through the slab shown in Figure 12.19. This detail focuses only on foundation items. Other items, such as exterior wall insulation, wall cladding, interior drywall, and so on, are not shown for clarity.

Figures 12.19 and 12.20 further explain the construction of a ribbed reinforced concrete (RC) slab-on-ground foundation. (The construction details relating to an RC slab-on-ground are presented in Chapter 22.)

EXTERIOR FOUNDATION WALLS, INTERIOR PIERS (SHORT COLUMNS), AND AN ELEVATED GROUND FLOOR

This foundation system, shown conceptually in Figure 12.2(a), is commonly used for light-frame buildings in cold climates, where, because of the deeper frost line, a slab-on-ground foundation cannot be used. It consists of strip footings under load-bearing exterior walls, Figure 12.21. As previously stated, the bottom of the footings must be below the frost line.

The ground floor framing members span from exterior wall to exterior wall, creating a crawl space below.

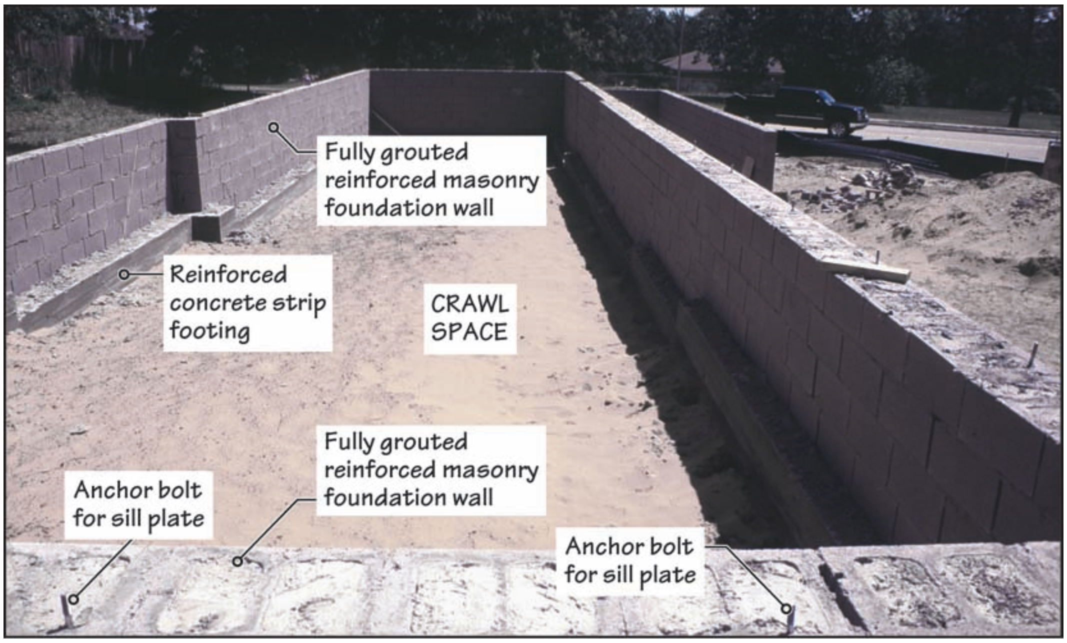

Fully grouted reinforced masonry foundation wall
Reinforced concrete strip footing
CRAWL SPACE
Fully grouted reinforced masonry foundation wall
Anchor bolt for sill plate
Anchor bolt for sill plate

FIGURE 12.21 The foundation system of this single-family house consists of perimeter foundation walls. In this building, the distance between the opposite foundation walls is small. This allows the ground floor framing members to span from exterior wall to exterior wall, precluding the need for intermediate support(s) of floor framing members (see Figure 12.22). The wall footings are partly exposed because adequate soil-bearing capacity was available at shallow depth below the ground.

If the distance between the opposite exterior walls is large, interior piers (short columns) are provided to support an intermediate beam. The beam reduces the span for the floor framing members, Figures 12.22 and 12.23. Additional details of this foundation system are shown in Figures 12.24 and 12.25.

WALL AND COLUMN FOOTINGS—REINFORCED CONCRETE SLAB AS THE GROUND FLOOR

In this foundation system, the concrete slab-on-ground is simply a floor that carries its own load plus the ground floor live load. It does not function as a foundation system for the structural members of the building, which must bear on their own footings, Figure 12.26. Isolation joints are required between the concrete slab-on-ground and the structural members so that the settlement of footings does not create stresses in the slab. (See Section 22.11 for a discussion of isolation joints.) Figure 12.27 provides additional details of this system.

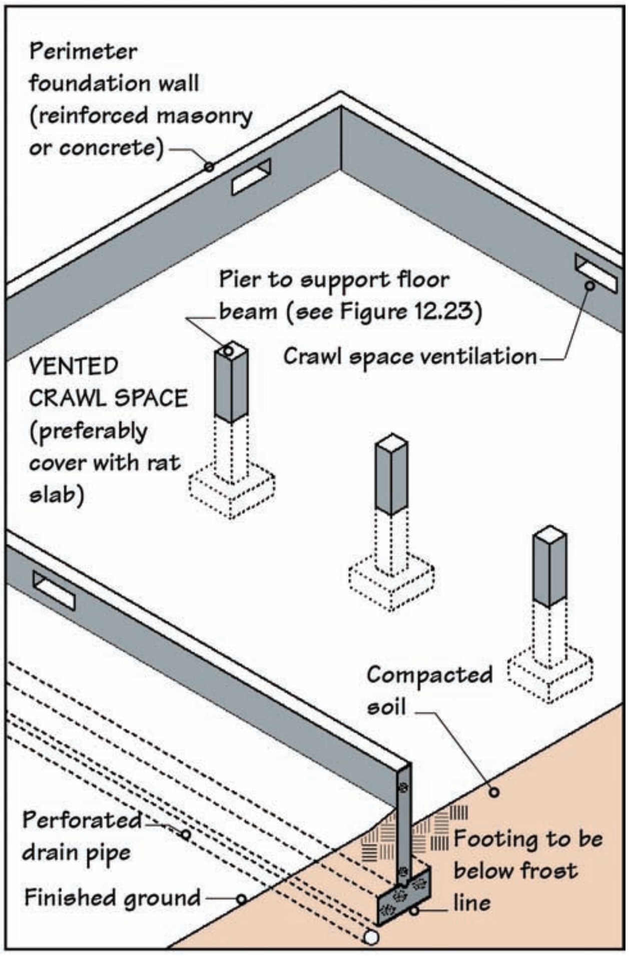

Perimeter foundation wall (reinforced masonry or concrete)
Pier to support floor beam (see Figure 12.23)
VENTED CRAWL SPACE (preferably cover with rat slab)
Crawl space ventilation
Compacted soil
Perforated drain pipe
Footing to be below frost line
Finished ground

FIGURE 12.22 An isometric of foundation system with footings under perimeter foundation walls and interior piers. The ground floor of such a building is generally constructed of wood frame with a crawl space below the floor. As good practice, the crawl space floor should be covered with "rat slab", see Expand Your Knowledge section "Requirements for Space Between an Elevated Ground Floor and Underlying Soil".

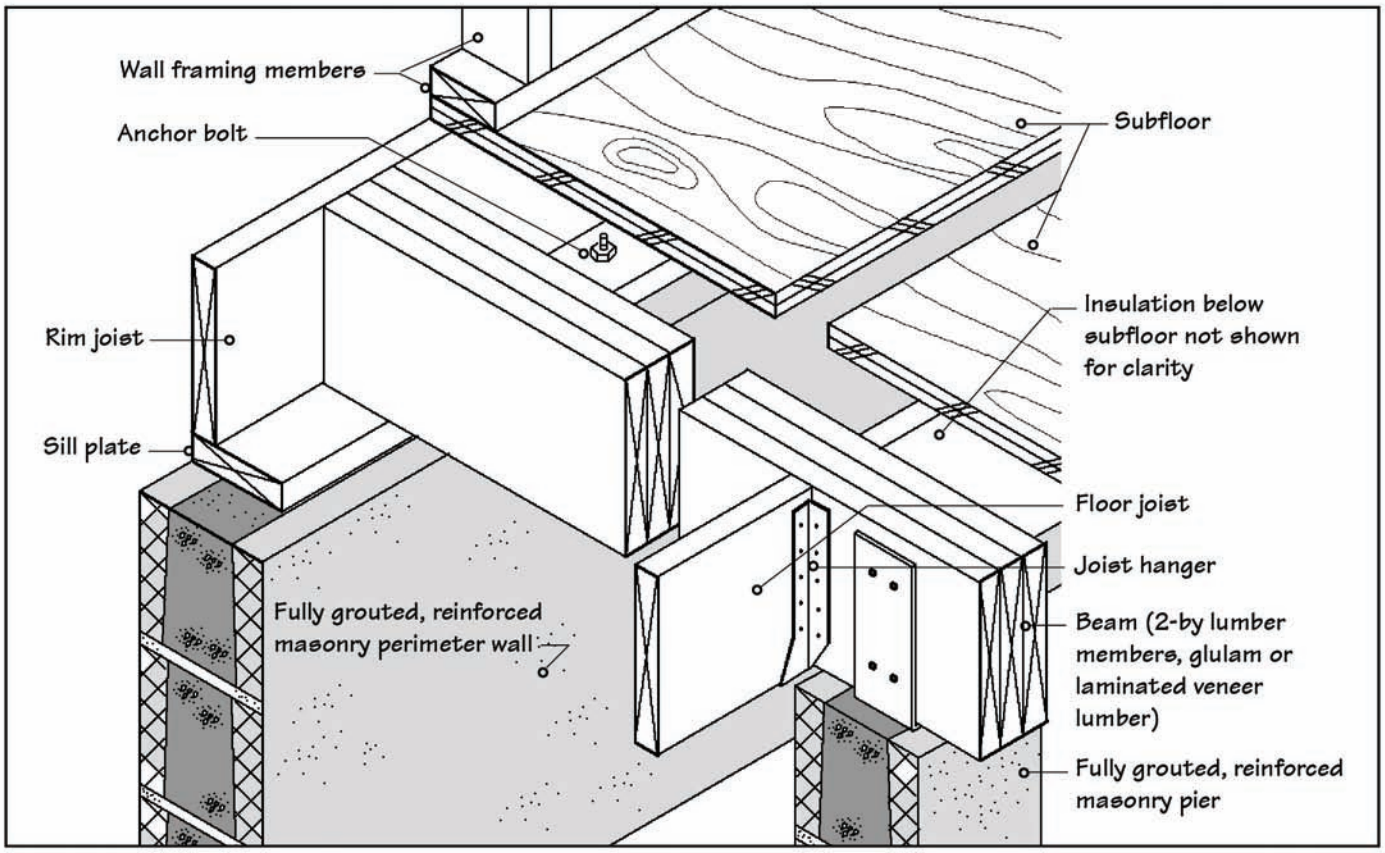

Wall framing members
Anchor bolt
Subfloor
Rim joist
Insulation below subfloor not shown for clarity
Sill plate
Floor joist
Joist hanger
Fully grouted, reinforced masonry perimeter wall
Beam (2-by lumber members, glulam or laminated veneer lumber)
Fully grouted, reinforced masonry pier

FIGURE 12.23 Isometric detail of the ground floor and foundation system shown in Figure 12.22.

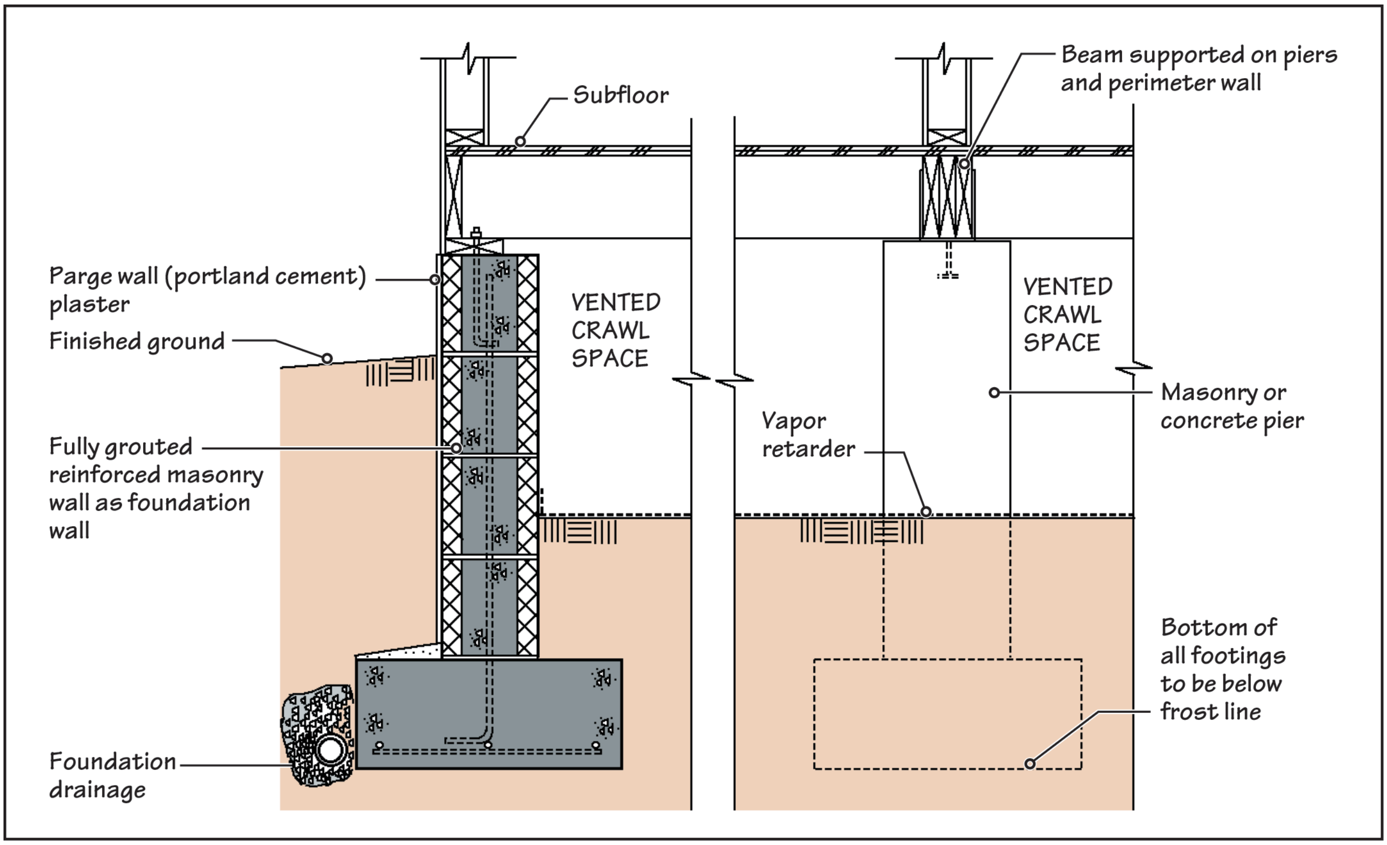

Subfloor
Beam supported on piers and perimeter wall
Parge wall (portland cement) plaster
Finished ground
VENTED CRAWL SPACE
VENTED CRAWL SPACE
Fully grouted reinforced masonry wall as foundation wall
Vapor retarder
Masonry or concrete pier
Bottom of all footings to be below frost line
Foundation drainage

FIGURE 12.24 Part section through the foundation system shown in Figure 12.23. This illustration focuses only on foundation items. Several other details, such as wall and floor insulation, exterior wall cladding, and so on, are not shown for clarity. (See also Expand Your Knowledge section "Requirements for the Space Between a Raised Ground Floor and the Underlying Soil".

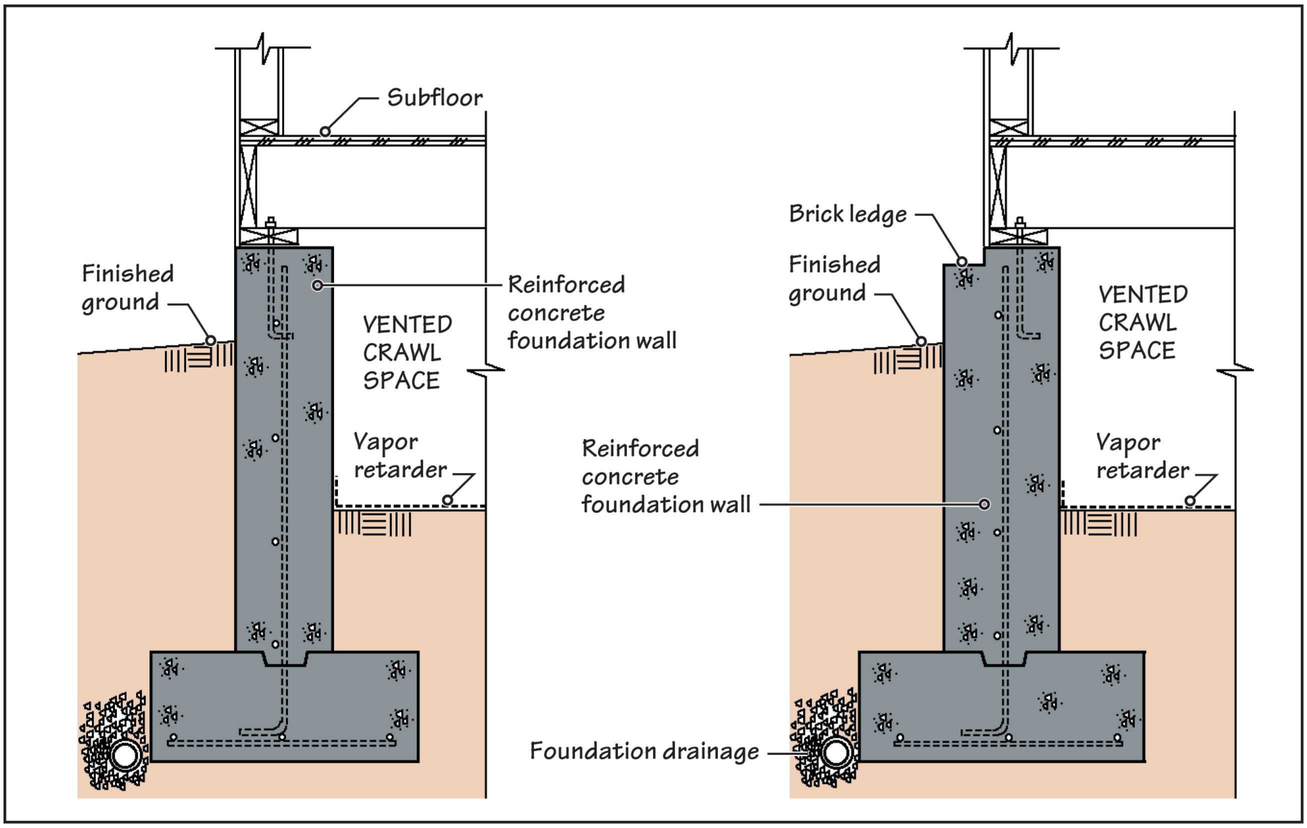
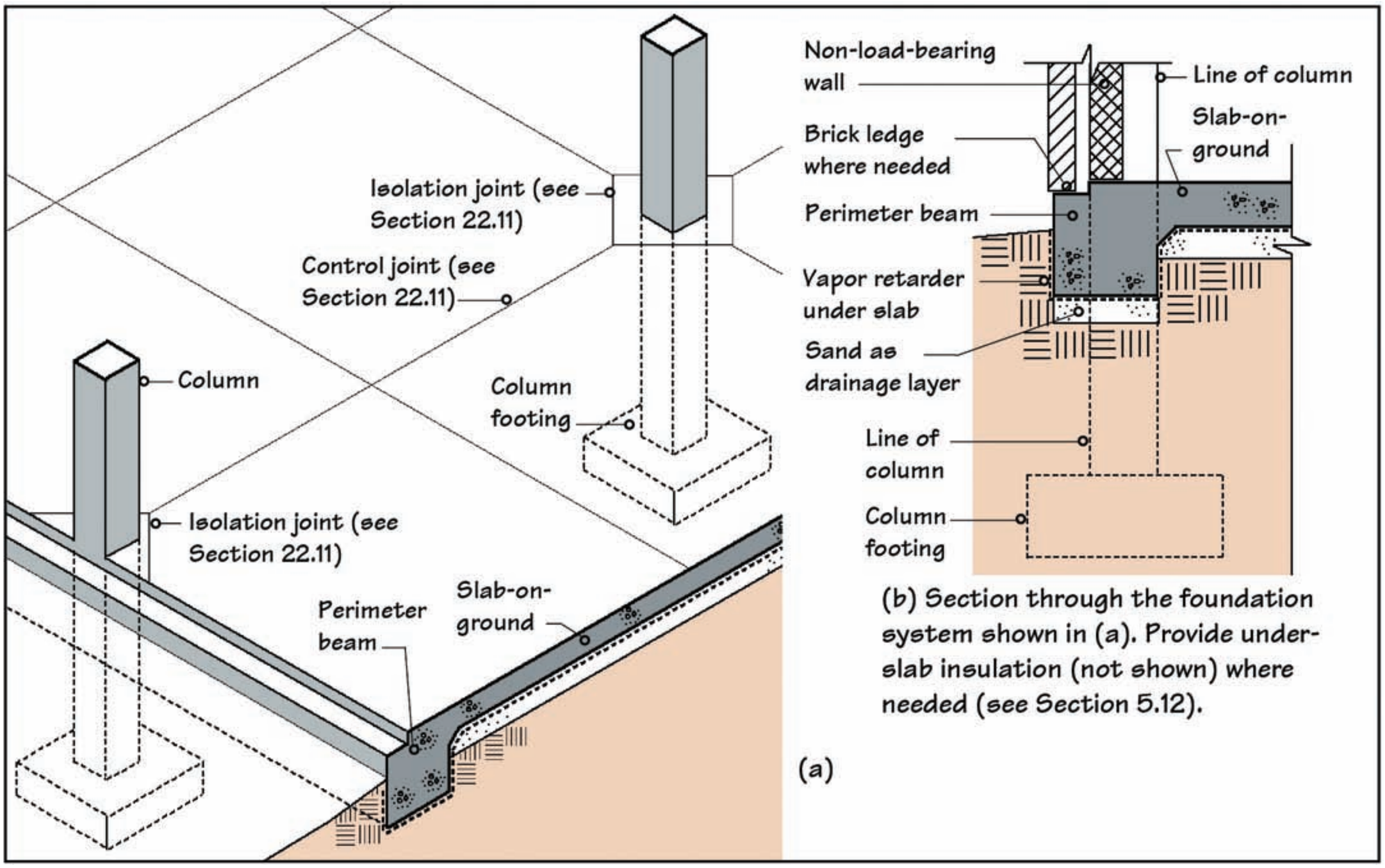
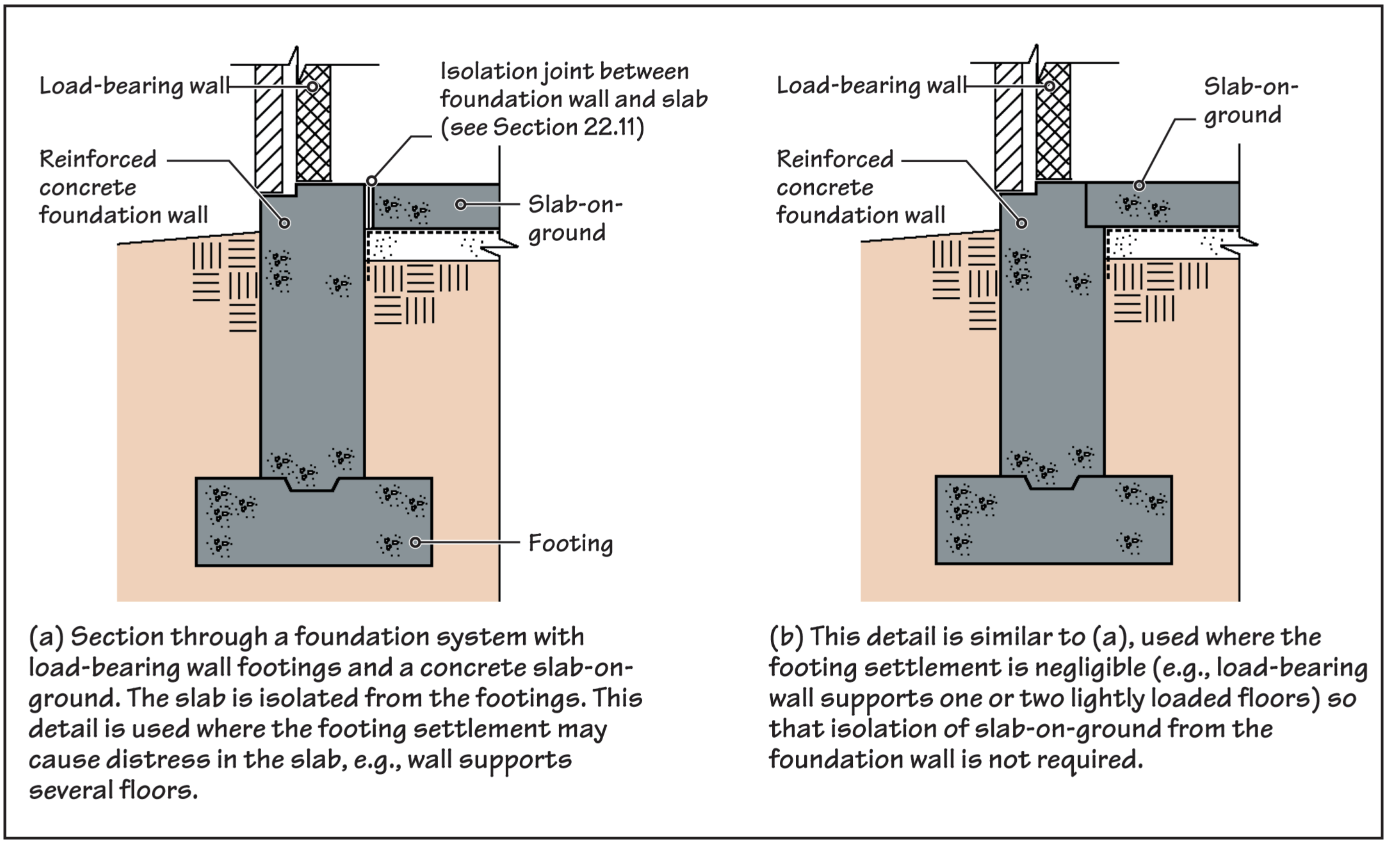

Subfloor
Finished ground
Reinforced concrete foundation wall
VENTED CRAWL SPACE
Vapor retarder
Brick ledge
Finished ground
VENTED CRAWL SPACE
Reinforced concrete foundation wall
Vapor retarder
Foundation drainage

FIGURE 12.25 Two alternative details of the foundation system shown in Figure 12.24. The alternatives shown here use reinforced concrete perimeter walls in place of reinforced concrete masonry walls.


Isolation joint (see Section 22.11)
Control joint (see Section 22.11)
Column
Column footing
Isolation joint (see Section 22.11)
Perimeter beam
Slab-on-ground
(a)
Non-load-bearing wall
Line of column
Slab-on-ground
Brick ledge where needed
Perimeter beam
Vapor retarder under slab
Sand as drainage layer
Line of column
Column footing

(b) Section through the foundation system shown in (a). Provide under-slab insulation (not shown) where needed (see Section 5.12).

FIGURE 12.26 Foundation system for a building with isolated columns and non-load-bearing perimeter walls. Non-load-bearing walls are supported on a reinforced concrete slab-on-ground. Note that isolation joints are required between columns and slab-on-ground.


Load-bearing wall
Isolation joint between foundation wall and slab (see Section 22.11)
Reinforced concrete foundation wall
Slab-on-ground
Footing
Load-bearing wall
Slab-on-ground
Reinforced concrete foundation wall

(a) Section through a foundation system with load-bearing wall footings and a concrete slab-on-ground. The slab is isolated from the footings. This detail is used where the footing settlement may cause distress in the slab, e.g., wall supports several floors.

(b) This detail is similar to (a), used where the footing settlement is negligible (e.g., load-bearing wall supports one or two lightly loaded floors) so that isolation of slab-on-ground from the foundation wall is not required.

FIGURE 12.27 Foundation systems for buildings with load-bearing wall footings and concrete slab-on-ground floors.

EXPAND YOUR KNOWLEDGE

Requirements for the Space Between a Raised Ground Floor and the Underlying Soil

As described in this chapter, the ground floor structure in many buildings is not supported on the ground but is raised above it, creating a space between the ground floor and the underlying soil. This space may be made accessible or left inaccessible, depending on the floor's structural frame or the requirements of any mechanical, electrical, and plumbing (MEP) systems installed under the floor.

Accessibility of Below-Floor Space

A raised ground floor structure made of wood or steel framing members is liable to deteriorate due to the buildup of moisture in the space below the floor. (Wood is impacted by fungal decay and steel by corrosion. Termite infestation is an additional concern for wood frame members.) With such a ground floor structure, an accessible crawl space is essential because it allows inspection and repair of the floor structure.

If the floor structure consists of cast-in-place reinforced concrete, the above concerns do not exist. Therefore, the space under a raised reinforced concrete floor need not be accessible.

An accessible below-floor space is referred to as *crawl space*. Building codes prescribe minimum dimensions of access opening for an accessible crawl space.

Control of Moisture Buildup in Below-Floor Space

Apart from the effect of below-floor moisture on the structural members, its entry (in the form of water vapor) into the space above the ground floor is a concern. Therefore, adequate control of below-floor moisture is required, regardless of the type of structural frame. Building codes require that the buildup of moisture in this space be controlled. Two alternatives are provided: (a) ventilate below-floor space or (b) provide a vapor retarder.

Minimum ventilation requirements, and the protection of ventilators against the entry of insects into below-floor space, are prescribed by the building codes. If a vapor retarder is used for moisture control, it must cover the entire surface below the floor. The joints between the vapor retarder membranes must be lapped and sealed, and the membrane must be turned up and anchored to the perimeter foundation walls, columns, and other obstructions.

Generally, if the space below the ground floor is accessible (i.e., a crawl space), both alternatives (ventilation and a vapor retarder) are recommended for redundancy and improved performance.

Rat Slab and Crawl Space

To make the crawl space easier to crawl on, a good practice is to provide a 2-in.-thick, lightly unreinforced concrete slab over a vapor retarder. The slab also helps to deter pests, such as mice and roaches, and hence is commonly known as a *rat slab*.

12.8 DETAILS OF FOUNDATION SYSTEMS ON EXPANSIVE SOILS

Commonly used foundation systems for low-rise buildings on expansive soils are listed below. As stated in the introduction to this chapter, most of these systems may also be used where soils have a low bearing capacity or are otherwise unsuitable (e.g., have excessive organic content).

- Posttensioned concrete slab-on-ground foundation
- Grade beams and drilled piers with (elevated) ground floor over a crawl space
- Grade beams and drilled piers with a suspended concrete ground floor slab
- Drilled piers with a suspended concrete ground floor slab

POSTTENSIONED (PT) CONCRETE SLAB-ON-GROUND FOUNDATION

If the soil is highly expansive, the slab-on-ground must be made so stiff that it floats on the soil as a raft—the entire foundation responding to the soil's swelling and shrinkage as one monolithic unit. Although a reinforced concrete slab-on-ground can be designed to accomplish this objective, it becomes quite uneconomical (even a ribbed reinforced concrete slab is uneconomical) compared with a posttensioned (PT) concrete slab-on-ground.

A PT concrete slab-on-ground foundation is similar to a ribbed reinforced concrete slab-on-ground foundation except that high-strength steel reinforcements (called *tendons*) are used in place of normal steel. A PT slab also consists of perimeter beams and intermediate beams in both directions, and a finished PT concrete slab-on-ground looks identical to that of a reinforced concrete slab-on-ground foundation (shown in Figures 12.19 and 12.20).

Posttensioning introduces compression in the slab, which not only stiffens the slab but also prevents the development of cracks that are inherent in a reinforced concrete slab. Thus, a PT concrete slab-on-ground does not require control joints. (The construction of PT concrete slabs-on-ground is discussed in Chapter 22.)

GRADE BEAMS AND DRILLED PIERS WITH (ELEVATED) GROUND FLOOR OVER A CRAWL SPACE

A foundation system that is considered more reliable on expansive soils than a PT concrete slab-on-ground is one that uses drilled piers to transfer building loads to a stable stratum while passing through the expansive zone (see Figure 12.10). In this foundation system, the piers terminate a small distance above the ground level where they support a network of grade beams.

The grade beams support the ground floor structure of the building. Any superstructure columns and load-bearing walls are also supported on the piers, Figure 12.28. Because of the elevated ground floor, this foundation system results in an (accessible) crawl space.

Grade beams may be of concrete or steel, and the ground floor may be framed with wood, steel, or concrete, depending on the building's occupancy, durability, and fire-resistance requirements. Perimeter grade beams are generally of concrete and also serve as retaining walls for backfill. Figure 12.28 shows a foundation system where the interior grade beams are of structural steel supported by steel columns bearing on drilled piers. The ground floor framing is of steel as well.

Figures 12.29 and 12.30 show the foundation system of a residential building with cast-in-place reinforced concrete grade beams and wood floor. A section through this foundation system is shown in Figure 12.31. The foundation system shown in Figure 12.32 is that of a school building where the grade beams are of cast-in-place reinforced concrete and the ground floor is constructed of precast concrete hollow-core slabs.

Grade Beams and Drilled Piers With a Suspended Concrete Ground Floor Slab

The provision of a crawl space has the advantage of providing easier access for repair and maintenance of below-floor utility lines and HVAC ducts (where provided). However, it raises the ground floor elevation, requiring additional earthwork around the building. Therefore, where a crawl space is unnecessary, the foundation system shown in Figure 12.31 is modified to the one shown in Figure 12.33.

In this system, reinforced concrete grades beams, supported on drilled piers, are partially buried in the ground. The formwork for grade beams between the piers is provided by cardboard boxes (referred to as *void boxes*). The void boxes bear on the soil and are strong enough to withstand the weight of concrete and other construction loads. However, they decompose in time, leaving a clear space between the underside of the grade beams and the soil. This allows the soil to swell and shrink without imposing any pressure on the beams.

The grade beams support a cast-in-place reinforced concrete slab. The formwork for the slab is also provided by void boxes. Thus, after the void boxes have decomposed, a space is created between the slab and the soil, and the slab functions as a suspended slab. Note that the space between the soil and the slab is inaccessible.

This foundation system is structurally identical to an elevated reinforced concrete floor structure used in a multifloor reinforced concrete building (see Chapter 23).

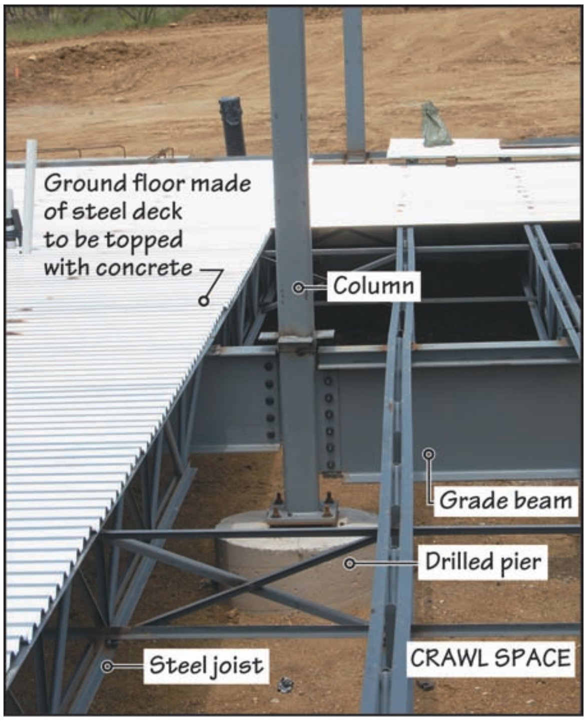


FIGURE 12.28 Foundation system of a building on expansive soil in which the columns and grade beams are supported on drilled piers. In this building, the perimeter grade beams (not shown) are made of reinforced concrete. Interior grade beams are made of structural steel. The ground floor of the building is framed with steel joists and steel deck.

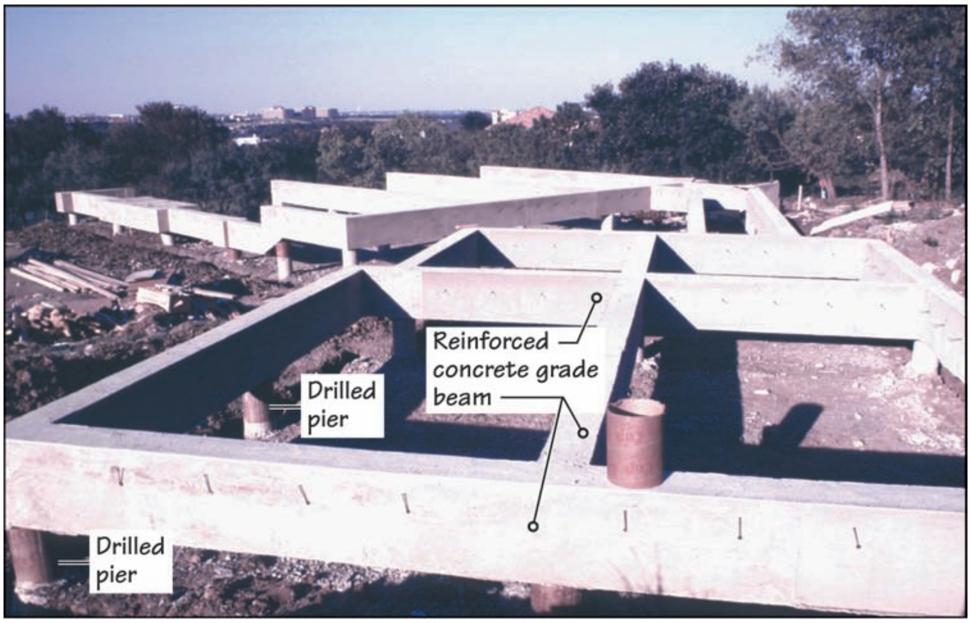


FIGURE 12.29 Foundation system beam comprising reinforced concrete grade beams supported by drilled piers. Grade beams support the ground floor framing, as shown in Figure 12.30. A crawl space is created between the ground floor framing and the underlying soil.

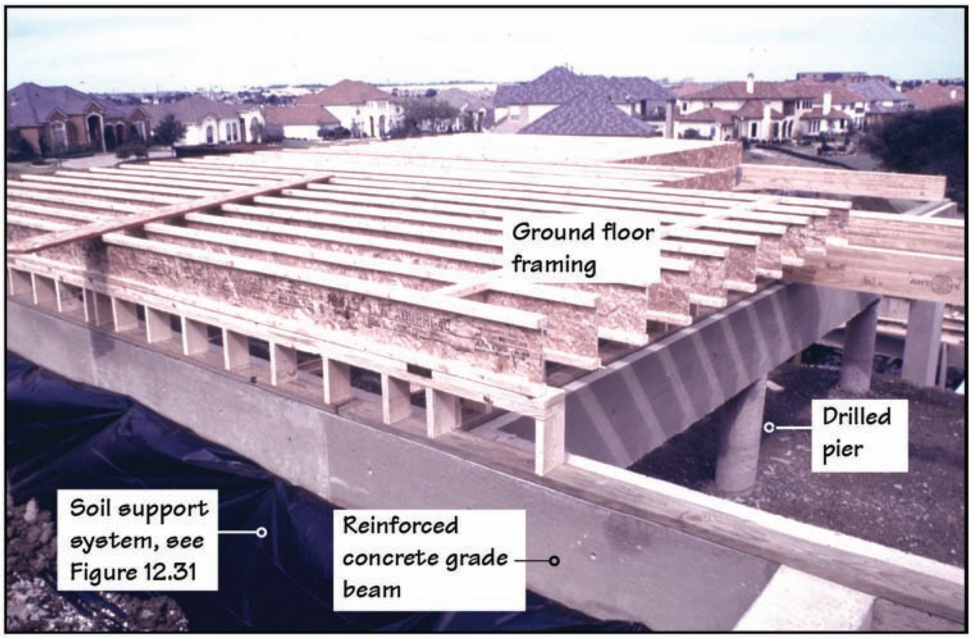

Ground floor framing
Drilled pier
Soil support system, see Figure 12.31
Reinforced concrete grade beam

FIGURE 12.30 This image shows the progress in the construction of ground floor framing (consisting of wood light-frame members) over the foundation system shown in Figure 12.29.

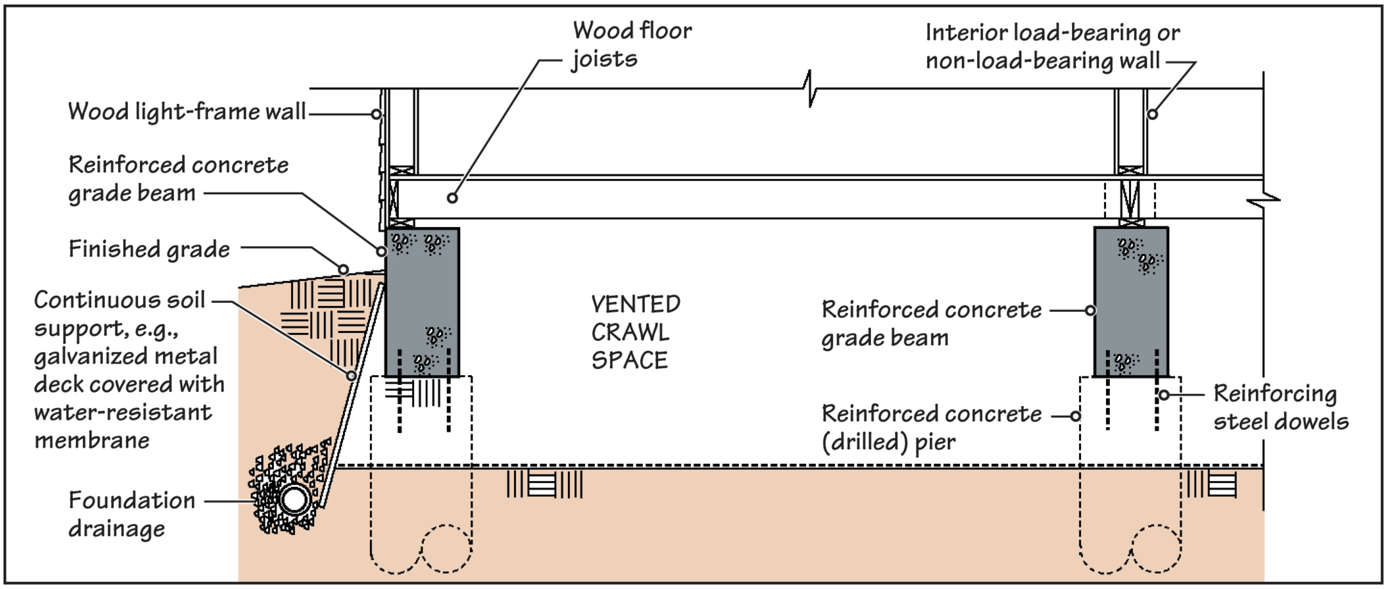

Wood floor joists
Interior load-bearing or non-load-bearing wall
Wood light-frame wall
Reinforced concrete grade beam
Finished grade
Continuous soil support, e.g., galvanized metal deck covered with water-resistant membrane
Foundation drainage
VENTED CRAWL SPACE
Reinforced concrete grade beam
Reinforced concrete (drilled) pier
Reinforcing steel dowels

FIGURE 12.31 Part section through the foundation system shown in Figure 12.30. Note that the focus of this detail is only on foundation items. For clarity, several other items are not shown.

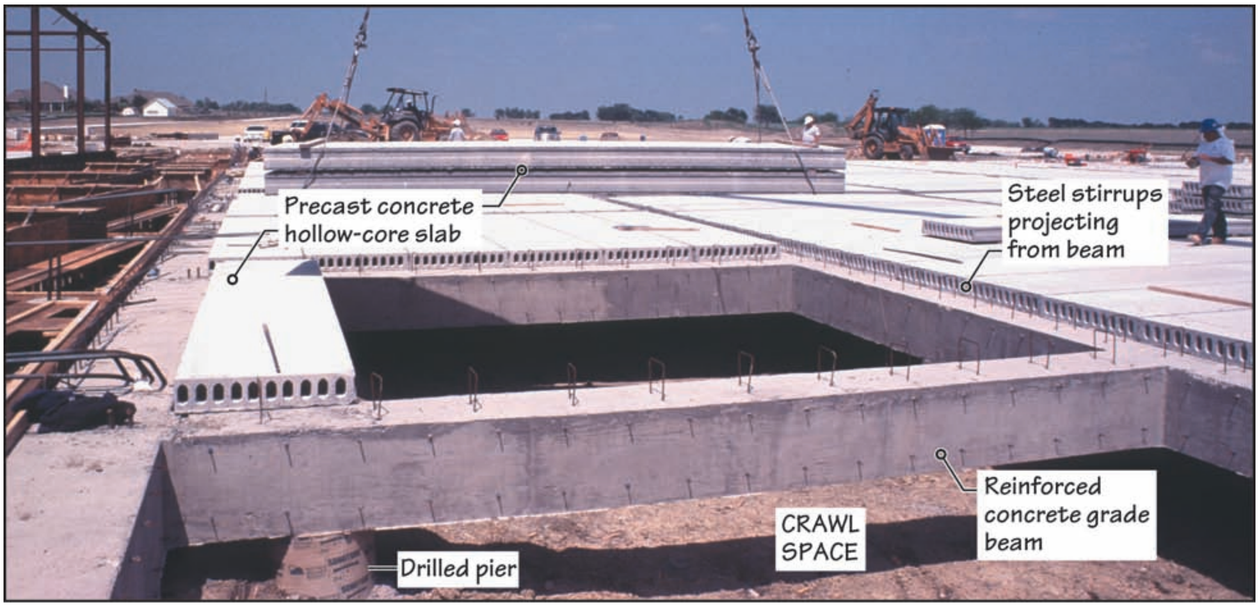

Precast concrete hollow-core slab
Steel stirrups projecting from beam
Reinforced concrete grade beam
CRAWL SPACE
Drilled pier

FIGURE 12.32 Foundation system comprising drilled piers and reinforced concrete grade beams. The ground floor consists of precast concrete hollow-core slabs. A layer of concrete will be placed over the entire floor system (grade beams and hollow-core slabs). Steel stirrups projecting from grade beams are intended to integrate all floor elements into one monolithic concrete floor.

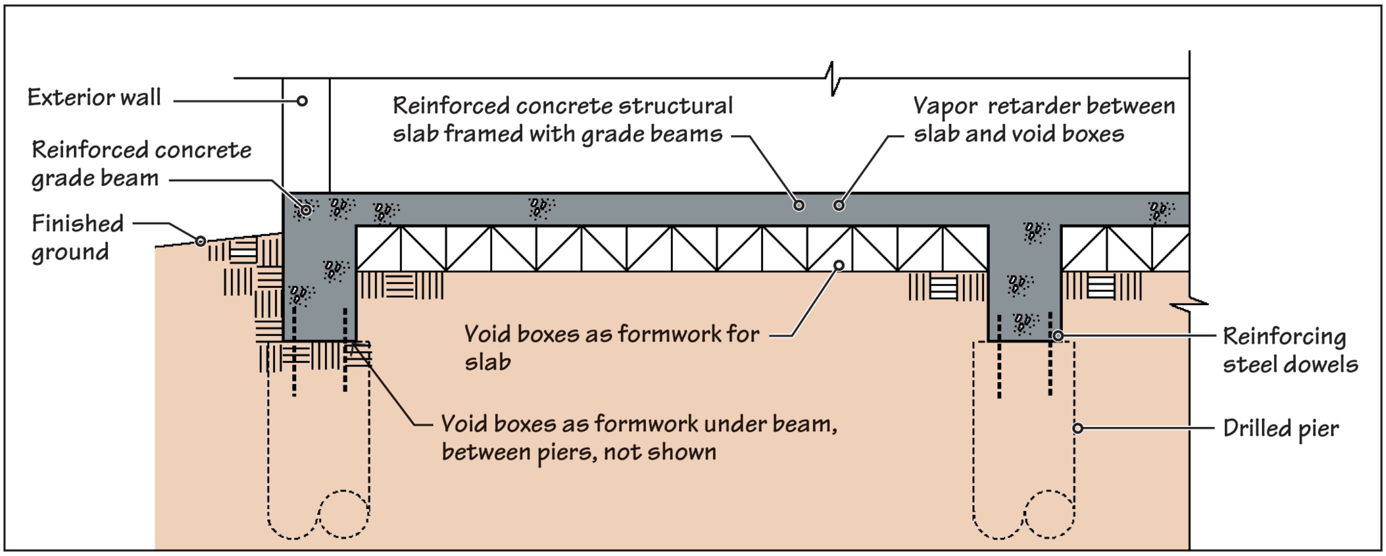

Exterior wall
Reinforced concrete grade beam
Finished ground
Reinforced concrete structural slab framed with grade beams
Vapor retarder between slab and void boxes
Void boxes as formwork for slab
Void boxes as formwork under beam, between piers, not shown
Reinforcing steel dowels
Drilled pier

FIGURE 12.33 Foundation system comprising grade beams and drilled reinforced concrete piers without a crawl space. The ground floor slab is not ground supported but is supported by grade beams as a suspended slab. Void boxes, made of cardboard, are used as formwork under the slab and grade beams. Void boxes decompose shortly after construction, leaving an (inaccessible) space under the slab and grade beams. This space allows the soil to swell and shrink without affecting the grade beams and slab.

DRILLED PIERS WITH A SUSPENDED CONCRETE GROUND FLOOR SLAB

Another foundation system uses a structural slab supported directly on drilled piers. The slab is thickened around the piers, Figures 12.34 to 12.36. Void boxes under the slab function as the formwork. Grade beams are provided at the perimeter only to support exterior wall loads. Structurally, this foundation system is identical to an elevated flat slab floor (see Chapter 23).

12.9 BASEMENT CONSTRUCTION AND WATERPROOFING

The term *basement* refers to an enclosed space that is below the ground floor of the building. A residential basement is generally one floor deep, with a floor height of 8 ft to 10 ft, with the top of the basement wall terminating approximately 2 ft to 3 ft above the finished ground level. On a sloping site, the basement floor may be above the ground level on one or two sides, referred to as a *walk-out* or *daylight basement*. Residential basements are more common in colder regions of the United States, where the frost line is deep so that a basement can be economically provided without much additional excavation. Commercial basements can be several floors deep, particularly in buildings located in downtown areas.

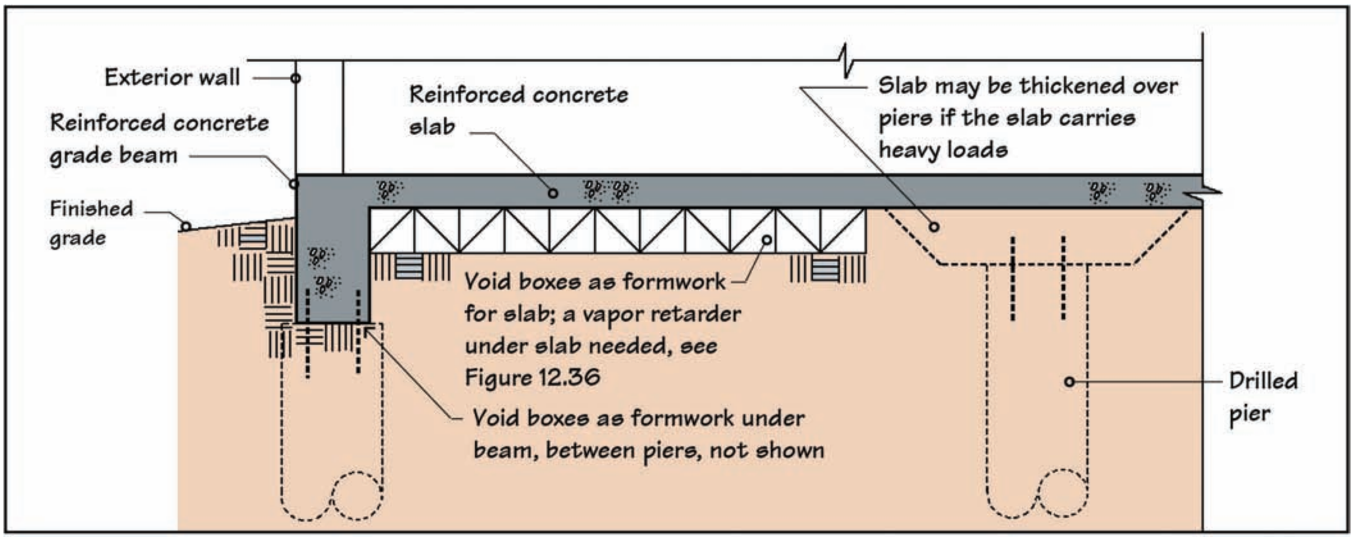

Exterior wall
Reinforced concrete grade beam
Finished grade
Reinforced concrete slab
Slab may be thickened over piers if the slab carries heavy loads
Void boxes as formwork for slab; a vapor retarder under slab needed, see Figure 12.36
Void boxes as formwork under beam, between piers, not shown
Drilled pier

FIGURE 12.34 Foundation system in which the concrete slab-on-ground is thickened around the piers. Grade beams are generally provided at the perimeter of the building to support exterior walls. Structurally, this ground floor slab is similar to elevated flat slab floor, see Section 23.3. For a slab with normal loads on it, thickening is unnecessary, as shown in Figure 12.35.

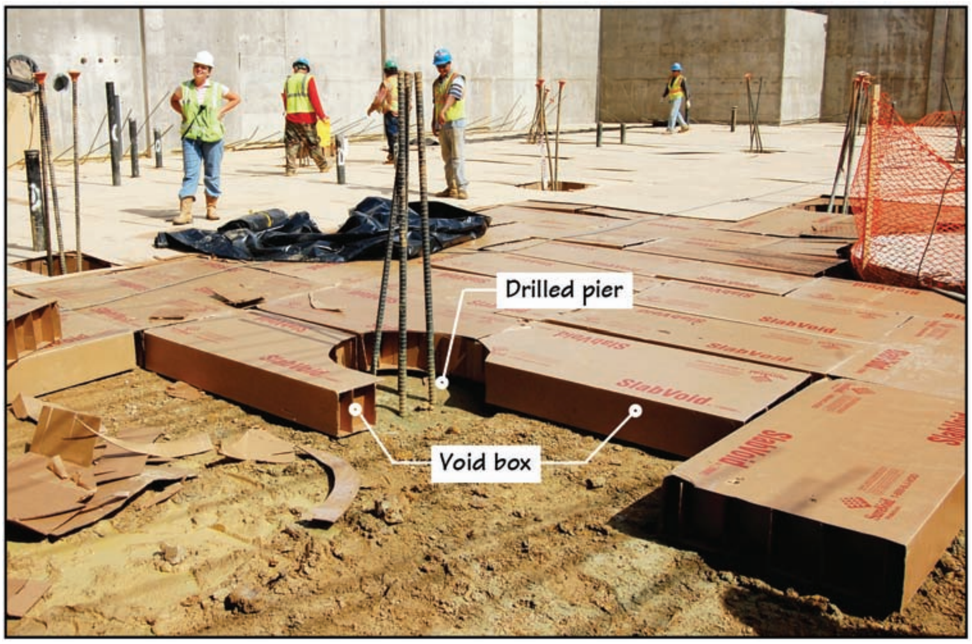


FIGURE 12.35 Cardboard void boxes provide the formwork for the reinforced concrete slab-on-ground. They have adequate strength to carry construction loads and the weight of wet concrete in the slab. Over time, the void boxes decompose leaving a space between the slab and the ground, which allows the underlying soil to shrink and swell freely without affecting the slab. Thus, the slab does not rest on the ground but on the columns supported on drilled piers. Structurally, this system is identical to an elevated flat plate floor slab (see Section 23.3). The void boxes will be covered with a 1/4-in.-thick plywood (seen in the background) and a vapor retarder before the reinforcement is placed (see Figure 12.36).

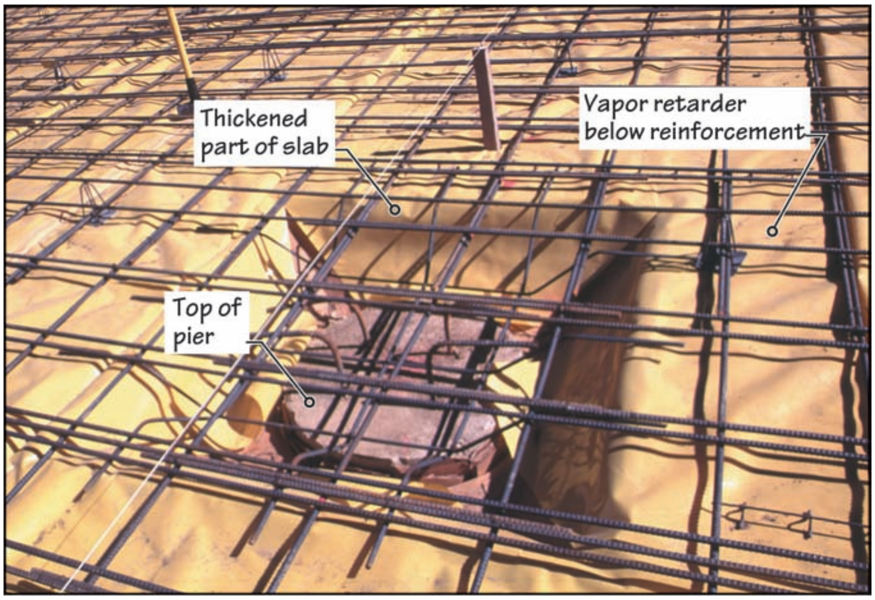


FIGURE 12.36 The foundation system of Figure 12.37. Note that the slab is thickened around the perimeter.

CONDITIONED AND UNCONDITIONED BASEMENTS

A basement can be conditioned (to maintain a constant indoor temperature) or unconditioned, where the indoor temperature fluctuates with the outdoor temperature. For a conditioned basement, insulation may be required under the basement slab. The basement walls generally require insulation only up to 10 ft below the finished ground level (see Section 5.12).

Basement walls may be insulated from the inside or the outside. In a multilevel commercial basement, the insulation is required only for the upper basement level. Therefore, in such basements, interior insulation is common. In residential basements, which are only one level deep, outside placement of insulation (over the entire depth of the basement) is common. Note that outside insulation is more effective (see Section 5.16).

The walls of an unconditioned basement should be insulated the same way as those of a conditioned basement. However, a lower R-value insulation may be justified. The ceiling of an unconditioned basement should be insulated as per the local energy code. Generally, this insulation is placed between the ground-floor framing members.

STRUCTURAL CONSIDERATIONS

The major structural components of a residential basement are the walls and the floor. Cast-in-place reinforced concrete is the most commonly used material for both walls and the floor of contemporary basements, although reinforced masonry and pressure-treated wood may be used for the walls. Basement walls must be designed to withstand lateral earth pressure and gravity loads from the upper floors. A section through a typical reinforced concrete residential basement is shown in Figure 12.37. Wall footings consist of strip footings and are cast first, followed by basement walls and the basement slab.

BASEMENT WATERPROOFING

Waterproofing is obviously the most important consideration for basements. It is applied to both the basement walls and the floor. For the walls, it is applied on the outside; for the floor, it is applied under it so that it forms a continuous, unbroken barrier to the entry of water. In earlier times, the use of layers of hot coal-tar pitch or hot asphalt alternating with fiberglass felt to yield a 3- to 5-ply membrane was the most common basement-waterproofing technique—a technique identical to that used for built-up roofing today (Chapter 33).

Although a hot-tar or asphalt system is easily applied on a horizontal surface, its application on a vertical surface is difficult. Safety concerns are critical in underground waterproofing because of the limited working space available. Therefore, a hot-applied waterproofing system has largely been replaced by cold-applied systems.

Commonly used cold-applied, below-grade waterproofing systems are similar to single-ply roof membranes and consist of rubberized asphalt or thermoplastic sheets. The sheets, usually 60 mil (1.5 mm) thick, are available in self-adhering rolls with a release paper. Before the sheets are applied, the basement wall and floor surfaces are cleaned and primed with the manufacturer's primer. Because the sheets are self-adhering, they form a continuous waterproof membrane.

In place of membrane waterproofing, liquid-applied elastomeric compounds may be used, which can be sprayed on, rolled on, or brushed on. They are particularly attractive for complex surface formations but are prone to application errors.

BASEMENT DRAINAGE

The basement drainage system is an important component of basement waterproofing. Its purpose is to collect, drain, and discharge groundwater away from the building. The drainage system consists of drainage mats and a drain pipe. The drainage mats have a thick open-weave structure that allows the subsoil water to drain downward by gravity. They eliminate or reduce water pressure acting on a below-grade wall and also protect the waterproofing layer and/or insulation from damage that might be caused by the backfill.

In a typical basement, waterproofing is applied directly to (the outside of) the basement wall, followed by insulation and, finally, the drainage mat, Figure 12.37. Some manufacturers provide the drainage mats laminated to extruded or expanded polystyrene board.

The drain pipe used under for basement drainage is identical to the one used for foundation drainage—a 4-in. to 6-in.-diameter perforated pipe set within a bed of crushed stone that allows the water to seep into the pipe (Section 12.6).

POSITIVE-SIDE, NEGATIVE-SIDE, AND BLIND-SIDE WATERPROOFING

The waterproofing layer shown in Figure 12.37 is called *positive-side waterproofing* because it has been applied on the side of the wall with direct exposure to water. *Negative-side waterproofing* refers to waterproofing that is applied from the opposite side, that is, from the interior. Negative-side waterproofing is generally used in remedial applications.

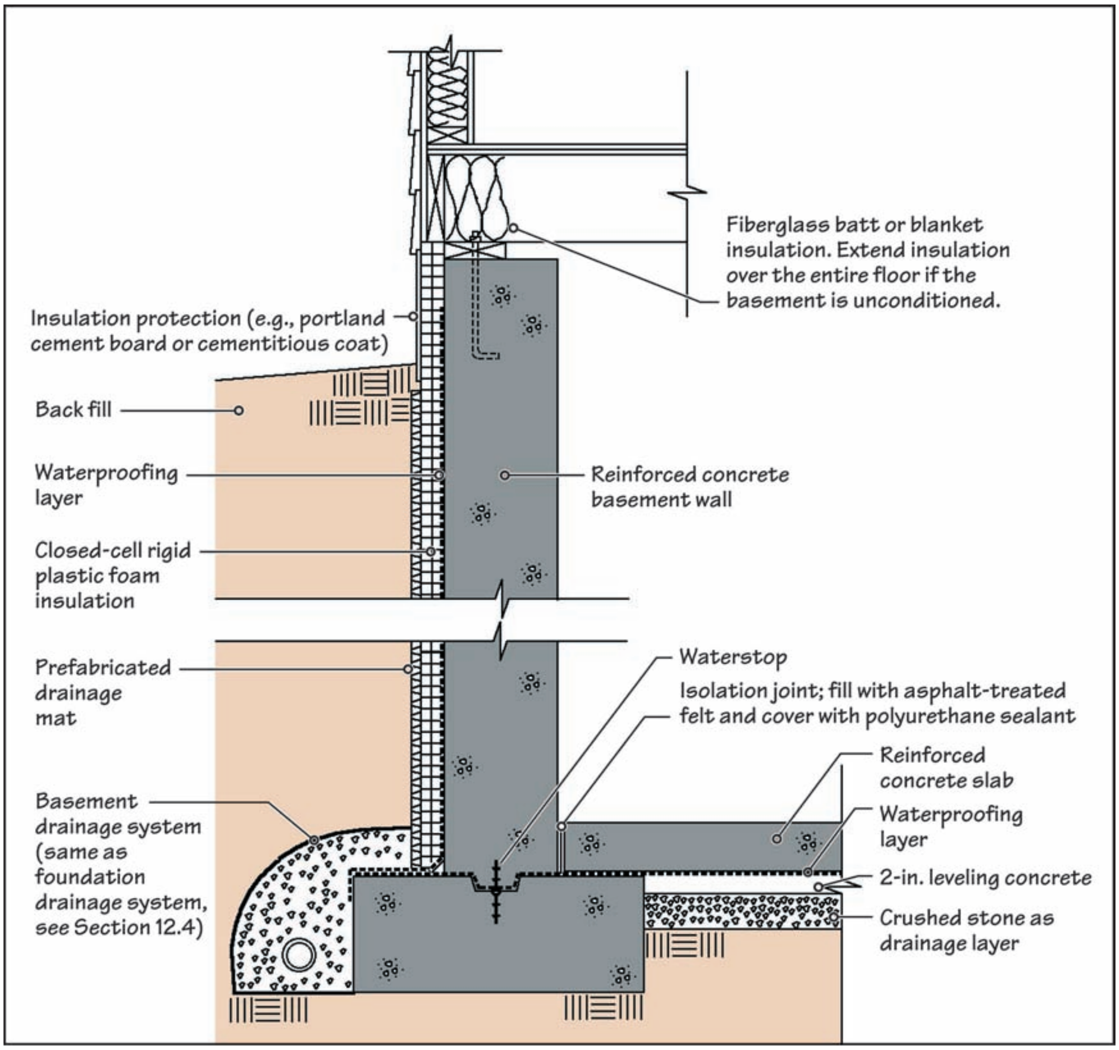

Fiberglass batt or blanket insulation. Extend insulation over the entire floor if the basement is unconditioned.
Insulation protection (e.g., portland cement board or cementitious coat)
Back fill
Waterproofing layer
Reinforced concrete basement wall
Closed-cell rigid plastic foam insulation
Prefabricated drainage mat
Waterstop
Isolation joint; fill with asphalt-treated felt and cover with polyurethane sealant
Reinforced concrete slab
Basement drainage system (same as foundation drainage system, see Section 12.4)
Waterproofing layer
2-in. leveling concrete
Crushed stone as drainage layer

FIGURE 12.37 Section through a typical residential basement constructed with an open excavation system (see Figure 11.9). Although a reinforced concrete wall is shown here, it can be replaced by a reinforced masonry wall.

EXPAND YOUR KNOWLEDGE

Soil Treatment Under Foundations Against Termites

The soil under and around building foundations must be treated with a termicide to prevent damage by termites. Because termites live in underground colonies, the treated soil creates a toxic barrier where the termites perish in trying to reach the building.

The treatment consists of spraying a waterborne chemical into the soil before constructing the foundations. The chemicals are regulated by the U.S. Environmental Protection Agency (EPA) and should be applied by a specialized and bonded company. The efficacy of the treatment is of a limited duration depending on the chemical and its concentration; it may need to be reapplied a few times during the building's life. Therefore, the treatment done before the building's construction is called *pretreatment*.

Although pretreatment is critical for wood structures, it must be applied to all buildings, regardless of the materials used in their structural frame (steel, concrete, masonry, etc.). It may be omitted in climates where termite infestation is not a concern, such as extremely cold or extremely arid climates.

Pretreatment of soil is only one of several measures needed to protect the building against termites. Additional measures are needed particularly for wood frame buildings, as discussed in Section 13.14.

Positive-side waterproofing is more effective and is more commonly used. It also protects the wall against water seepage, mold growth, metal corrosion, and so on. It requires adequate space outside a below-grade wall for applicators to work, which is later backfilled. Positive-side waterproofing, therefore, remains accessible after its completion.

Blind-side waterproofing refers to waterproofing applied to the outside of the wall that becomes inaccessible after the wall's construction. It is used in situations where the basement wall is supported by an excavation-support system such as soldier piles and lagging, which are left in place. In this situation, the drainage mat and waterproofing layer are applied to the excavation-support system and the basement wall is constructed against it.

Blind-side waterproofing manufacturers provide the drainage mat and waterproofing layer integrated into one membrane. In this composite material, the waterproofing layer faces the interior; that is, fresh concrete for the basement wall is placed against the waterproofing layer. The drainage mat is in contact with the excavation-support system. Figures 12.38 and 12.39 illustrate blind-side waterproofing application.

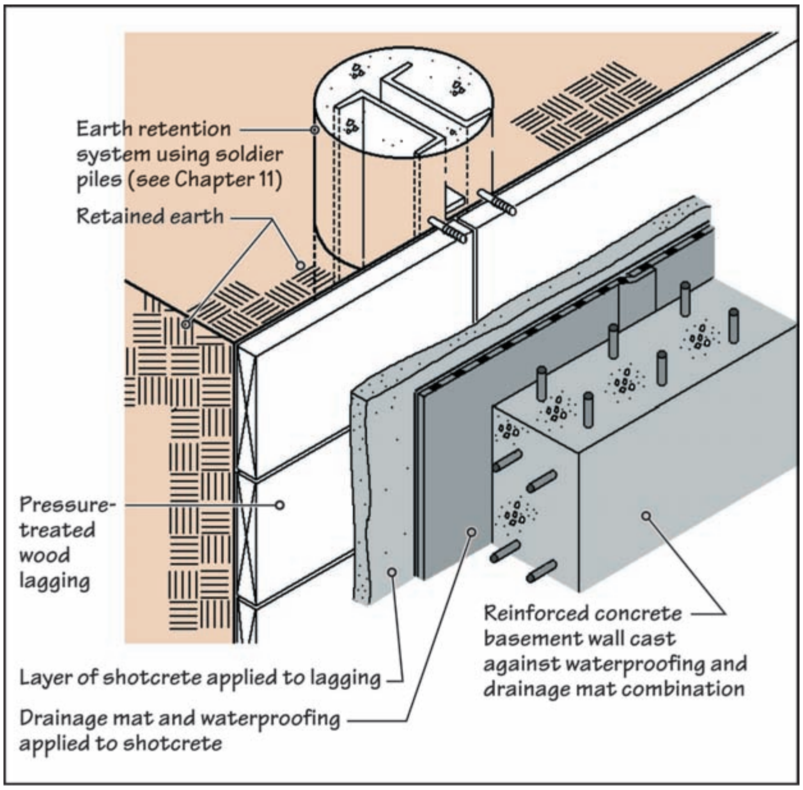

Earth retention system using soldier piles (see Chapter 11)
Retained earth
Pressure-treated wood lagging
Layer of shotcrete applied to lagging
Drainage mat and waterproofing applied to shotcrete
Reinforced concrete basement wall cast against waterproofing and drainage mat combination

FIGURE 12.38 Waterproofing of a reinforced concrete basement wall cast against a soldier pile and lagging system of excavation support (blind-side waterproofing).

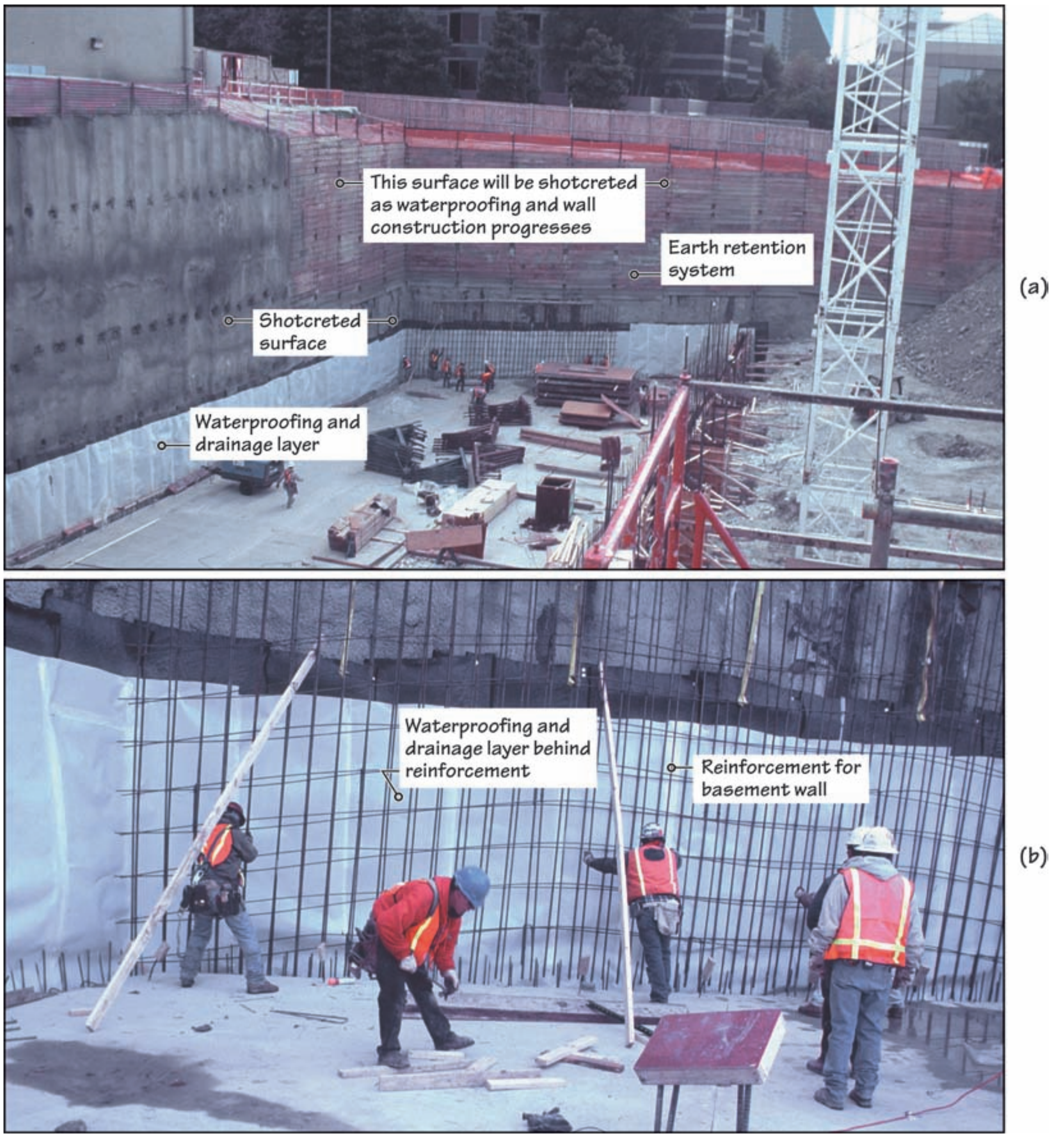

This surface will be shotcreted as waterproofing and wall construction progresses
Earth retention system
Shotcreted surface
Waterproofing and drainage layer
(a)
Waterproofing and drainage layer behind reinforcement
Reinforcement for basement wall
(b)

FIGURE 12.39 **(a)** In this deep basement, part of the cut face has been shotcreted. The shotcreted face is treated with waterproofing and a drainage mat layer. Additional shotcreting on the earth retention system will be done as construction of the reinforced concrete basement wall progresses. **(b)** After installation of waterproofing and the drainage mat, reinforcement is laid for the basement wall. This will be followed by wall formwork and concrete placement.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

17. A commonly used foundation drainage system consists of
- **a.** a perforated drain pipe.
- **b.** a perforated drain pipe set within a layer of crushed stone or gravel.
- **c.** a perforated drain pipe set within a layer of crushed stone or gravel, the layer wrapped with a filter fabric.
- **d.** a perforated drain pipe wrapped with filter fabric and set within a layer of crushed stone or gravel.
- **e.** any one of the above.

18. A reinforced concrete slab-on-ground foundation is suitable for
- **a.** lightly loaded low-rise buildings on stable soils.
- **b.** lightly loaded low-rise buildings on expansive soils.
- **c.** lightly loaded low-rise buildings on both stable and expansive soils.
- **d.** all types of buildings on stable soils, provided that it is at least 12 in. thick.
- **e.** all types of buildings on stable soils, provided that it comprises perimeter and intermediate beams in both directions.

19. A ribbed reinforced concrete slab-on-ground foundation is preferred over a constant-thickness slab foundation because
- **a.** its formwork is simpler.
- **b.** it can be constructed more quickly.
- **c.** it provides the same strength and stiffness at a lower cost.
- **d.** it does not require control joints.
- **e.** all of the above.

20. A foundation system consisting of perimeter foundation walls and an elevated ground floor with an underlying crawl space is commonly used
- **a.** where the soil is expansive.
- **b.** where the soil-bearing capacity is low.
- **c.** where the water table is high.
- **d.** for low-rise buildings in warm climates.
- **e.** for low-rise buildings in cold climates.

21. A posttensioned (PT) concrete slab-on-ground foundation generally consists of
- **a.** a PT slab, perimeter beams, and intermediate beams.
- **b.** a PT slab and perimeter beams.
- **c.** a PT slab only.
- **d.** any one of the above, depending on the superimposed loads.
- **e.** none of the above.

22. A PT concrete slab-on-ground foundation does not require control joints.
- **a.** True
- **b.** False

23. A PT concrete slab-on-grade foundation is commonly used
- **a.** on stable soils.
- **b.** on expansive soils.
- **c.** on soils with a high water table.
- **d.** all of the above.

24. A foundation system consisting of grade beams bearing on drilled piers and an elevated ground floor with an underlying crawl space is
- **a.** suitable for lightly loaded low-rise buildings on stable or high-bearing-capacity soils.
- **b.** suitable for lightly loaded low-rise buildings on expansive or low-bearing-capacity soils.
- **c.** suitable for all types of buildings on expansive or low-bearing-capacity soils.
- **d.** suitable for all types of buildings on stable or high-bearing-capacity soils.
- **e.** suitable for all types of buildings on all types of soils.

25. Void boxes used for concrete formwork in foundation systems are made of
- **a.** wood.
- **b.** steel.
- **c.** fiberglass.
- **d.** plastic.
- **e.** none of the above.

26. A foundation system consisting of perimeter grade beams and a reinforced concrete slab thickened over drilled piers is suitable
- **a.** where the soil is expansive.
- **b.** where the soil-bearing capacity is high.
- **c.** where the water table is high.
- **d.** for low-rise buildings in cold climates.
- **c.** for buildings with unconditioned interiors.

27. In a building with a foundation system consisting of grade beams bearing on drilled piers and an elevated ground floor with an underlying crawl space, the ground floor is generally constructed of
- **a.** wood frame.
- **b.** steel frame.
- **c.** precast concrete.
- **d.** any one of the above.
- **e.** none of the above.

28. Waterproofing that is applied to the outside of basement walls is called
- **a.** positive-side waterproofing.
- **b.** negative-side waterproofing.
- **c.** blind-side waterproofing.
- **d.** either positive-side or negative-side waterproofing.
- **e.** either positive-side or blind-side waterproofing.

29. In a basement excavation with walls supported by an excavation retention structure, waterproofing is applied to the excavation retention structure.
- **a.** True
- **b.** False

REVIEW QUESTIONS

1. With the help of sketches and notes, describe various foundation systems that cover the entire footprint of the building.
2. What is the difference between shallow foundations and deep foundations? Where would you recommend the use of deep foundations? Explain.
3. What is a casing, and where is it commonly used? Explain.
4. Using sketches and notes, describe the anatomy of a reinforced concrete slab-on-ground foundation.
5. Using sketches and notes, describe at least one type of foundation system used for low-rise buildings on stable soils.
6. Using sketches and notes, describe at least one type of foundation system used for low-rise buildings on unstable soils.
7. Explain what a rat slab is and where it is likely to be used.
8. Explain why the buildup of moisture in a crawl space must be controlled and what measures are commonly employed to achieve this goal.

CHAPTER 13

Materials for Wood Construction–I (Lumber)

CHAPTER OUTLINE

13.1 INTRODUCTION

13.2 GROWTH RINGS AND WOOD'S MICROSTRUCTURE

13.3 SOFTWOODS AND HARDWOODS

13.4 FROM LOGS TO FINISHED LUMBER

13.5 DRYING OF LUMBER

13.6 LUMBER SURFACING

13.7 NOMINAL AND ACTUAL DIMENSIONS OF LUMBER

13.8 BOARD FOOT MEASURE

13.9 SOFTWOOD LUMBER CLASSIFICATION

13.10 LUMBER'S STRENGTH AND APPEARANCE

13.11 LUMBER GRADING

13.12 DURABILITY OF WOOD

13.13 FUNGAL DECAY

13.14 TERMITE CONTROL

13.15 PRESERVATIVE-TREATED WOOD

13.16 FIRE-RETARDANT-TREATED WOOD

There are many structural and nonstructural applications for wood products in building construction. Because *wood* is a general term, it is important to clarify the terminology for its various uses.

The term *lumber* applies to wood products derived directly from logs through sawing and planing operations only, with no further manufacturing except cutting to length or finger jointing two or more pieces (see Section 13.6 for a discussion of finger jointing). In other words, only solid pieces of wood are classified as lumber. Hence, the terms *lumber, solid lumber, solid sawn lumber*, and *sawn lumber* are used synonymously.

In recent years, manufactured wood products—products manufactured with altered or transformed wood fibers—have been developed. These products are identified by their individual names and are not called lumber. Plywood was one of the earliest of these products.

Glue-laminated lumber, parallel strand lumber, and laminated veneer lumber are products that have the same or similar profiles as solid lumber, but are classified as manufactured wood products because their manufacturing process is more complex than that required for classification as lumber. Wood trusses and I-joists are other examples of manufactured wood products. These products have been formulated primarily to conserve the decreasing supplies of high-quality solid lumber members.

This chapter and the following four chapters deal with wood construction. The properties and uses of various wood products are presented first. Lumber is discussed in this chapter and manufactured wood products in Chapter 14. In practice, lumber and manufactured wood products are used together in the same building. Wood light-frame construction, a common construction system utilizing lumber and manufactured wood products, is described in Chapter 15. Chapter 16 deals with frequently used exterior and interior finishes in wood light-frame buildings. Chapter 17 deals with panelized wood frame construction in what is referred to *as structural insulated panel* (SIP) construction.

13.1 INTRODUCTION

One of the major advantages of wood as a building material is its renewability. Theoretically, all materials are renewable. However, wood is a building material that is renewed within the human time span. Trees for most softwood construction lumber are harvested within 25 to 40 years. Other naturally occurring building materials (stone, iron, aluminum, copper, etc.) are also renewed, but within geological time spans—in thousands or millions of years.

In order to optimize wood's renewablility, sufficient forest land must be available to grow trees, and the land must be carefully managed (lumber farming). Unfortunately, due to high population densities, the availability of land for lumber farming is severely limited in most parts of Africa, Asia, Europe, and Latin America. Coincidentally, forest-management skills are also relatively underdeveloped in these countries.

Wood used in buildings is, therefore, grown primarily in the less densely populated countries—the United States, Canada, Australia, New Zealand, Russia, and a few countries in Latin America. It is in these countries that wood is a major building and structural material today. The native wood in most other countries is used for nonstructural purposes, such as doors, windows, furniture, and cabinets.*

WOOD AND OTHER STRUCTURAL MATERIALS

Many believe that wood is the weakest of the structural materials, the others being concrete, masonry, and steel. This is true only in absolute terms. When viewed in relation to its density (unit weight), the strength of wood compares well with even the strongest of all building materials, steel. Weight for weight, wood's structural properties are almost comparable with those of steel (see Table 13.1).

For instance, the average unit weight of structural wood (lumber) is nearly 35 lb/ft^3, and its average allowable compressive strength (parallel to the grain) is 1.6 ksi. With a unit weight of 490 lb/ft^3, steel is nearly 14 times heavier than lumber, and its allowable compressive strength of nearly 30.0 ksi is 19 times that of the allowable compressive strength of lumber.

The strength-to-weight ratio of lumber in comparison with concrete and masonry is heavily in lumber's favor. For instance, the density of concrete (145 lb/ft^3) is approximately four times that of lumber, and the allowable compressive strength of the commonly used concrete mixes is only slightly higher than that of lumber.

The high strength-to-weight ratio of lumber not only reduces the dead loads but also precludes the need for heavy equipment for lifting and hoisting building components during construction. These and other factors, such as its lower cost and the relatively simpler construction techniques associated with it, account for wood's popularity for several building types. In countries with abundant forest reserves, wood is used extensively for residential and low-rise commercial buildings and amusement structures.

TABLE 13.1 COMPARISON OF LUMBER AND STEEL AS STRUCTURAL MATERIALS

Density (lb/ft^3)	
Lumber	35
Steel	490
Density ratio = 1:14	
Allowable compressive strength (ksi)	
Lumber (parallel to grain)	1.6
Steel	30.0
Compressive strength ratio = 1:19	
Allowable tensile strength (ksi)	
Lumber (parallel to grain)	1.0
Steel	30.0
Tensile strength ratio = 1:30	
Modulus of elasticity (ksi)	
Lumber	1,700
Steel	29,000
Modulus of elasticity ratio = 1:17	

Values for wood refer to the stronger lumber species and grades (such as Southern pine No. 1). Note that the structural properties of lumber vary with grade, species, and cross-sectional dimensions. Values for steel refer to steel with a yield strength of 50 ksi.

13.2 GROWTH RINGS AND WOOD'S MICROSTRUCTURE

A tree consists of three essential parts: (a) root structure, (b) trunk, and (c) branches and the leaf system. The root structure stabilizes the tree, and the trunk provides the strength required to support the branches and leaves. In addition to providing stability and strength, the other important function of the root structure and trunk is to conduct water mixed with food (nutrients) from the soil to the leaves and branches.

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*In developing countries, a great deal of wood is used as household fuel.

EXPAND YOUR KNOWLEDGE

Photosynthesis and Respiration

The Processes That Make Wood a Rapidly Renewable Material

The growth of trees and plants occurs due to a natural process called *photosynthesis*. In this process, the water drawn from the soil and the environment reacts with the carbon dioxide in the air to produce a basic sugar (glucose), releasing oxygen. This reaction requires a tree or plant as the medium and the presence of light energy from the sun, hence the term *photosynthesis*, whose literal meaning is “to synthesize with the help of light”. In other words

$$\text{Carbon dioxide} + \text{water} \xrightarrow[\text{energy}]{\text{Light}} \text{glucose} + \text{oxygen}$$

$$6CO_2 + 6H_2O \xrightarrow[\text{energy}]{\text{Light}} C_6H_{12}O_6 + 6O_2$$

Glucose is subsequently converted into other organic molecules that comprise the tree—cellulose, hemicellulose, and lignin. Cellulose* and hemicellulose, which are chemically similar to glucose, constitute nearly two-thirds to three-quarters of the weight of wood in a tree. Cellulose and hemicellulose form the walls of wood cells, and lignin is the glue that binds the cells together.

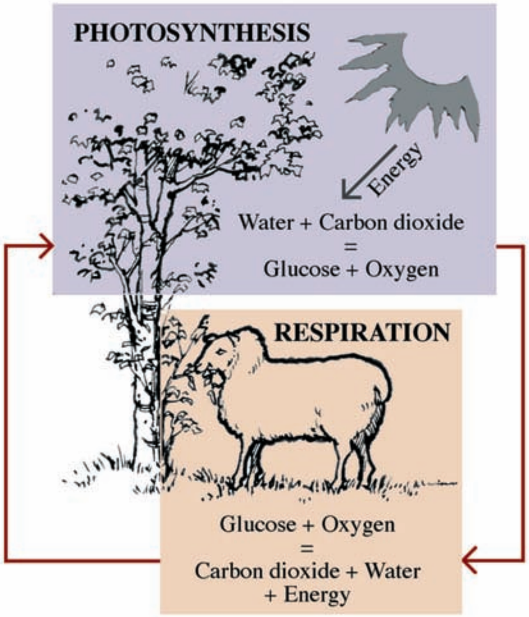
Although cellulose, hemicellulose, and lignin constitute the bulk of the wood, small quantities of other minerals and chemicals are also transported into the tree.

Photosynthesis is the reverse of *respiration*—a process by which the food that humans and animals eat is converted into sugar. This sugar is subsequently metabolized into carbon dioxide and water, and energy is released in this process:

$$\text{Glucose} + \text{oxygen} \rightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

Photosynthesis and respiration, being the reverse of each other, form an ecological cycle on which all terrestrial life depends.



The tree obtains water from the soil and carbon dioxide from the atmosphere and converts them into sugar (contained in plant life). This reaction, in which oxygen is released, requires the presence of energy that is supplied by the sun.

Animals, humans and other creatures consume the sugar in plants. With the help of oxygen that they breathe, they convert these substances into carbon dioxide (that they exhale) and water is given off in animal and human waste.

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*Chemically, a cellulose molecule is represented by $(C_6H_{10}O_5)_n$. The subscript n indicates that a cellulose molecule is a polymer consisting of several $C_6H_{10}O_5$ monomers linked together end-to-end as the loops in a chain. Typically, in a cellulose polymer, n may be as high as 10,000, which gives polymer lengths of nearly 0.01 mm. The orientation of the polymer chains along the long axis of the tree provides many of the basic properties of wood.

As water moves through the tree and reaches the leaves, it is converted to cellulose by *photosynthesis*. The transportation of water from the soil is accompanied not only by food, but also by several other dissolved minerals and chemicals in small quantities. Water transportation requires the microscopic structure of a tree to consist of tiny hollow tubes, referred to as *cells*. To transport food efficiently, the cells must be oriented along the long axis of the tree—vertically in the trunk and along the length of an individual branch. The cells are visible only when magnified several times under a microscope.

Figure 13.1 shows part of the unmagnified cross section through the trunk of a tree. The outermost dark-colored layer is the bark, followed by several increasingly smaller rings toward the center of the trunk. These rings are referred to as *annual rings*, because a new ring is typically added every year. *Growth ring* is, however, a better term because in some trees, more than one ring may be added per year.

The addition of growth rings occurs in the *cambium* layer, which lies between the bark and the outermost growth ring (Figure 13.1). The cells in the cambium layer divide and subdivide, producing the cells of the growth rings and the bark. As each growth ring is added, the girth of the tree increases.

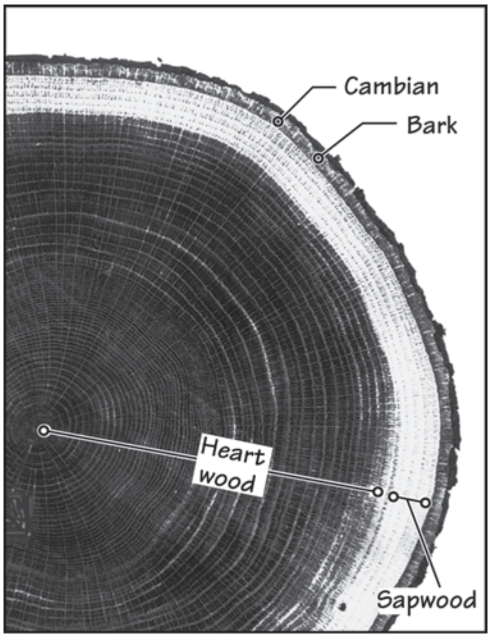


FIGURE 13.1 A cross section through the trunk of a tree. The cambium layer, in which cell division takes place, lies between the bark and the outermost growth ring. The interior dark-colored region is the heartwood, and the light-colored region is the sapwood. The radial lines (which are rather faint in this diagram) are the rays (Section 13.3). (Photo courtesy of the Forest Products Laboratory, U.S. Department of Agriculture)

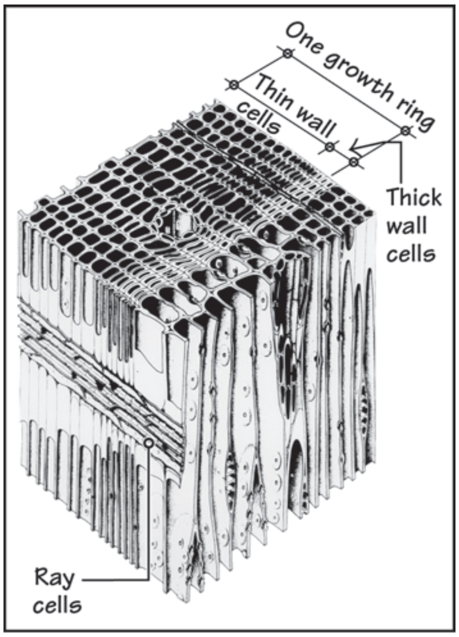


FIGURE 13.2 A magnified view of the cross section of a tree trunk. (Photo courtesy of the Forest Products Laboratory, U.S. Department of Agriculture)

NOTE

Earlywood and Latewood

The terms *springwood* and *summerwood* were used earlier for earlywood and latewood, respectively, which erroneously represented a connection with a calendar season of the year. In many tropical areas, which remain wet throughout the year, the growth of a tree occurs throughout the year.

EARLYWOOD AND LATEWOOD

The cells added during the wet season have thinner walls and larger cavities. During the dry season, when the tree has to transport less food, the cell walls are thicker and the cell cavities are smaller. The cells added during the wet and dry seasons are called *earlywood* and *latewood*, respectively.

It is the difference between the cells of earlywood and latewood that distinguishes each ring, Figure 13.2. The distinct growth rings give wood its characteristic grain structure.

In some species the difference between earlywood and latewood is less distinct than in others. For instance, in basswood, all cells have a similar wall thickness and cavity size, and the annual rings are indistinct. This yields wood with a relatively flat and even grain structure. By comparison, Southern yellow pine (Figure 13.3) has highly differentiated cell sizes, resulting in a pronounced grain structure.

HEARTWOOD AND SAPWOOD

As the tree ages and increases in girth, not all cells are needed to conduct food. As this happens, walls and cavities of the cells formed when the tree was younger (i.e., the rings closer to the center of the trunk) are impregnated with several chemical substances. This process increases the tree's mass and strength, which is required to support its increasing height.

The obvious manifestation of the chemical deposition is a change in the color of the wood. Thus, the growth rings added in the trunk earlier during the life of the tree are darker in color than those added later (Figure 13.1).

The darker-colored region of the trunk is referred to as the *heartwood*, and the lighter-colored region is called the *sapwood*. The word *sap* is just another term for the food that the tree conducts; hence, the term *sapwood* merely expresses the function of the light-colored outer growth rings in relation to the dark-colored inner rings. The change from sapwood to heartwood is gradual, and as the tree ages, the heartwood portion in the tree increases.

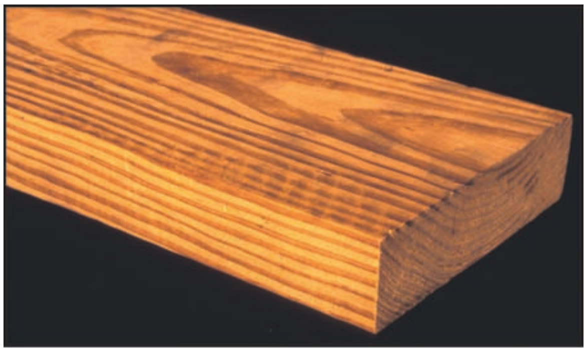


FIGURE 13.3 A piece of southern yellow pine illustrating its pronounced grain structure. By comparison, a piece of basswood, commonly used for architectural model making, has a flat, even grain structure.

The chemical deposition in many commercial trees is toxic to fungi. Therefore, the heartwood of most commercial trees is relatively more decay resistant than the sapwood. In some species, the decay resistance of the heartwood is significant. Before the introduction of pressure-treated wood, the heartwoods of redwood and cedar were commonly specified for lumber elements resting directly on concrete or masonry foundations, such as sill plates and sleepers.

Contemporary building codes also recognize the decay resistance of the heartwood of redwood and cedar by allowing them to be used where pressure-treated wood is required. The use of pressure-treated wood is, however, more common due to its greater decay and termite resistance.

13.3 SOFTWOODS AND HARDWOODS

Lumber is divided into two broad categories—*hardwoods* and *softwoods*. The hardwoods are generally denser than the softwoods. Because density is a major determinant of the strength of wood, hardwoods are generally stronger than softwoods.

The distinction between softwoods and hardwoods is, however, not based on the density of the wood, because several hardwoods are lighter than softwoods, and vice versa. For instance, balsa, among the lightest and weakest of woods, is a hardwood. On the other hand, slash pine and longleaf pine are softwoods but are denser than many hardwoods, Figure 13.4.

The distinction between softwoods and hardwoods is based on their botanical characteristics. Softwood-producing trees, in general, do not bear flowers and have a single main stem, and most of them are evergreen, with leaves that are needlelike (i.e., conical; hence, softwood trees are also called *conifers*), Figure 13.5. Pines, firs, spruces, cedars, hemlocks, and so on, are softwoods.

Hardwood-producing trees are generally flowering trees, have broad leaves, and are typically deciduous, shedding and regrowing leaves annually. Oak, walnut, birch, elm, teak, mahogany, rosewood, and so on, are hardwoods. Figure 13.6 shows a typical hardwood tree.

Softwoods in the United States come from two main regions, the western wood region and the southern pine region, and to a small extent from the northern and northeastern region, Figure 13.7. In addition to indigenous softwoods, a great deal of softwood lumber in the United States is imported from Canada. Most hardwoods in the United States are from the eastern region, ranging from New York to Georgia.

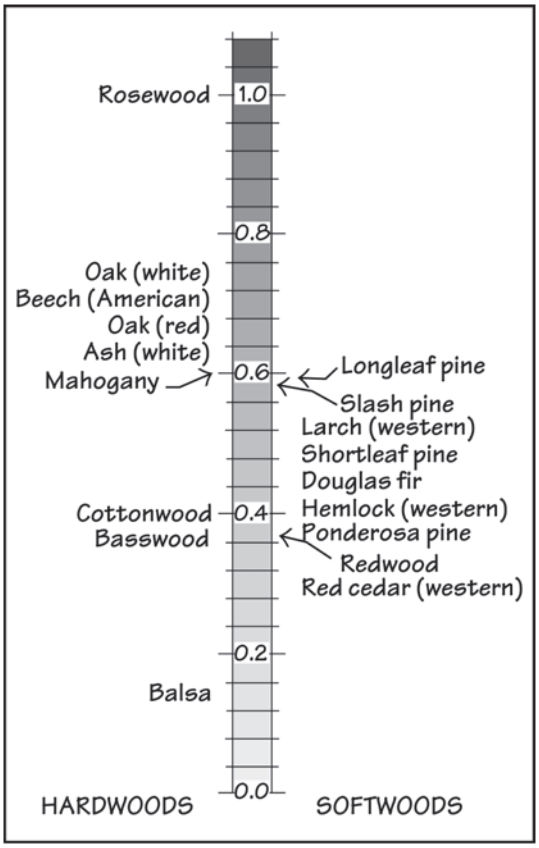


FIGURE 13.4 Specific gravities of selected softwoods and hardwoods.

MICROSTRUCTURE OF SOFTWOODS AND HARDWOODS

Although basically similar, there is some difference between the cellular structures of softwoods and hardwoods. In softwoods, all longitudinal cells are of the same type and almost the same size, Figure 13.8. These cells perform two functions: (a) provide strength to the tree and (b) conduct food from the ground up.

The cellular structure of hardwoods is more complex. Unlike softwoods, the longitudinal cells of hardwoods are of two types—one type with small cavities and the other with large cavities—with two distinct functions. The smaller cells in hardwoods provide strength to the tree, and the cells with larger cavities, referred to as *vessels*, conduct food, Figure 13.9. In many hardwoods, the vessels can be seen under an ordinary magnifying glass.

NOTE

Naturally Decay-Resistant Wood

Heartwood of redwood and cedar is naturally decay resistant and is recognized as such by the building codes.

NOTE

The Term *Species*

In this text, the term *species* is used in its customary sense, not in the botanically correct sense. In the botanist's language, a particular species is designated by the combination of *genus* (generic name) and *species* (specific name). For instance, the botanical name of Eastern white pine is *Pinus strobus*, in which *Pinus* represents the genus and *strobus* represents the species. Similarly, the botanical name of Ponderosa pine is *Pinus ponderosa*. For the sake of simplicity, the term *species* in this text includes both botanical terms—genus and species. Note also that the term *species* is used in both singular and plural forms.

NOTE

Specific Gravity

The specific gravity of a material is an index of its density relative to the density of water, that is, the density of the material divided by the density of water. Thus, if the density of a material is less than the density of water, its specific gravity is less than 1.0. Such a material will float on water. Conversely, if the density of a material is greater than the density of water, its specific gravity is greater than 1.0, and it will sink in water.

Because the density of water is 62.5 lb/ft^3, a wood whose specific gravity is 0.5 has a density of 31.25 lb/ft^3.

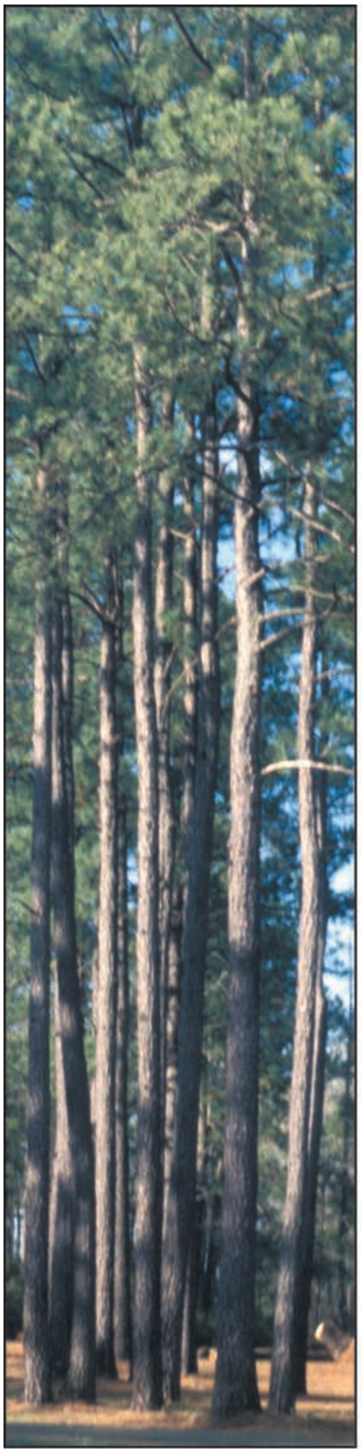
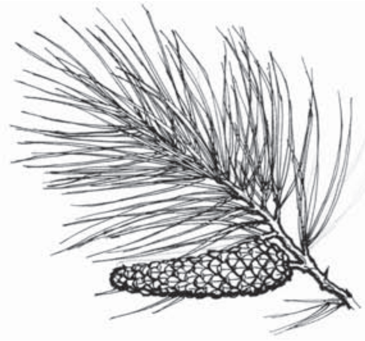
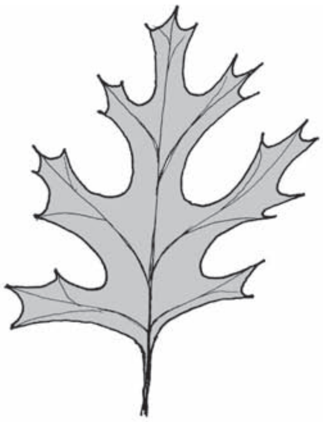


FIGURE 13.5 Softwood (pine) trees in the Willamette Industries forest, Ruston, Louisiana.


Pine cone with its scaled surface


Broad leaves of red oak

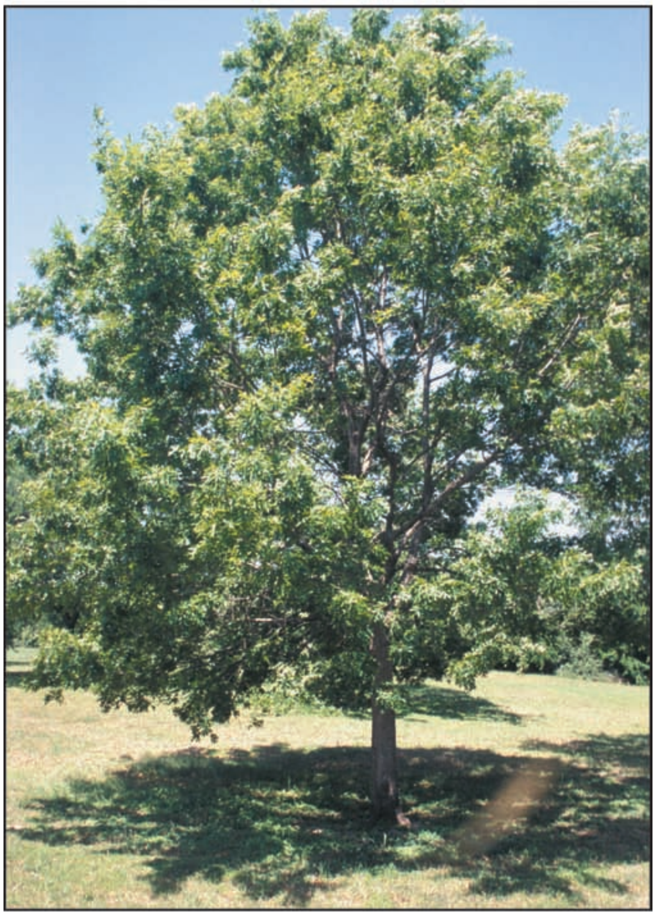


FIGURE 13.6 A hardwood tree (red oak).

In addition to the longitudinally oriented cells, both softwoods and hardwoods have transverse cells called *rays*. Rays are perpendicular to the longitudinal cells. They provide radial transfer of food, as well as transverse strength.

Ray cells are far more prominent in hardwoods than in softwoods. Due to the prominence of ray cells and the diversity of their longitudinal cells, most hardwoods show a more interesting grain structure than do softwoods.

WOOD'S ANISOTROPICITY

Despite the differences previously described, the microstructures of both softwoods and hardwoods are essentially similar and consist of a cluster of longitudinally oriented hollow tubes. This cluster resembles a bundle of drinking straws glued together and reinforced with a few transversely oriented tubes (ray cells), Figure 13.10. This simplification clarifies some of the important properties of wood.

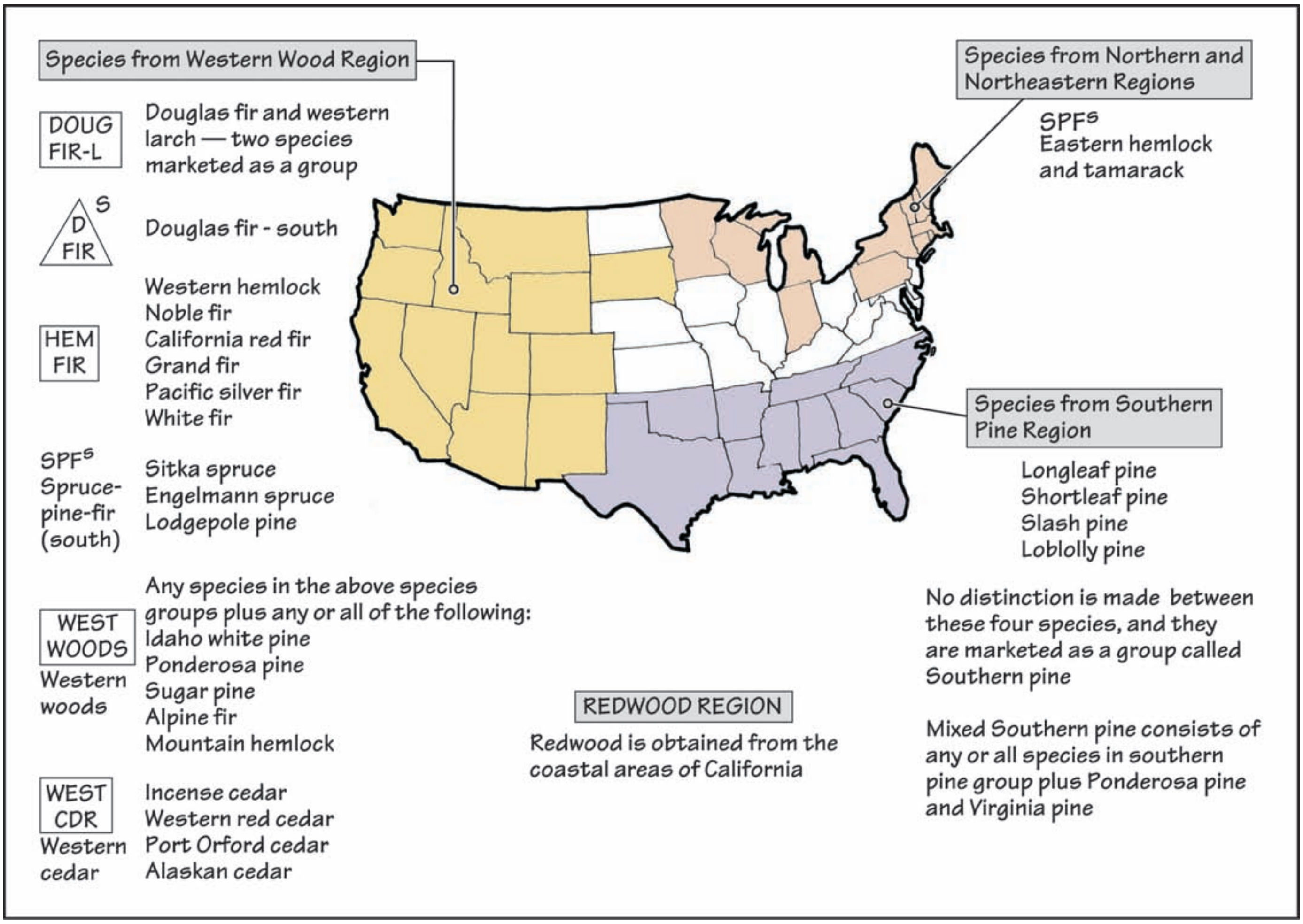

Species from Western Wood Region
DOUG FIR-L
Douglas fir and western larch — two species marketed as a group
S D FIR
Douglas fir - south
HEM FIR
Western hemlock
Noble fir
California red fir
Grand fir
Pacific silver fir
White fir
SPFs Spruce-pine-fir (south)
Sitka spruce
Engelmann spruce
Lodgepole pine
WEST WOODS Western woods
Any species in the above species groups plus any or all of the following:
Idaho white pine
Ponderosa pine
Sugar pine
Alpine fir
Mountain hemlock
WEST CDR Western cedar
Incense cedar
Western red cedar
Port Orford cedar
Alaskan cedar
Species from Northern and Northeastern Regions
SPFs
Eastern hemlock and tamarack
Species from Southern Pine Region
Longleaf pine
Shortleaf pine
Slash pine
Loblolly pine
No distinction is made between these four species, and they are marketed as a group called Southern pine
REDWOOD REGION
Redwood is obtained from the coastal areas of California
Mixed Southern pine consists of any or all species in southern pine group plus Ponderosa pine and Virginia pine

FIGURE 13.7 Map of the major softwood-producing regions in the United States showing the states included in each region.

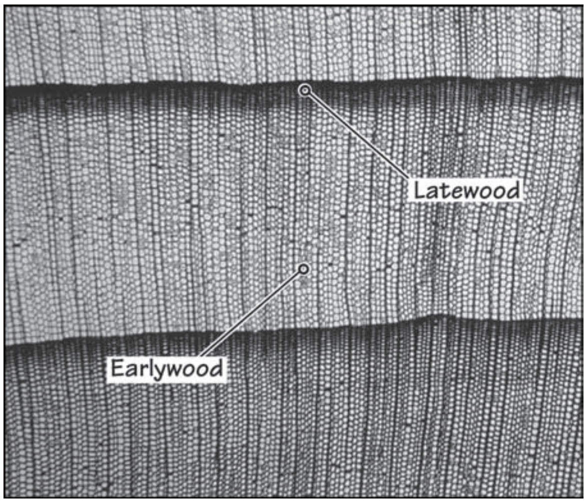

Latewood
Earlywood

FIGURE 13.8 Magnified view of a softwood's growth rings showing the cellular structure. The lighter-colored region, with larger cell cavities and thinner walls of a growth ring, represents earlywood. The darker-colored region with smaller cell cavities and thicker walls represents latewood. (Photo courtesy of the Forest Products Laboratory, U.S. Department of Agriculture)

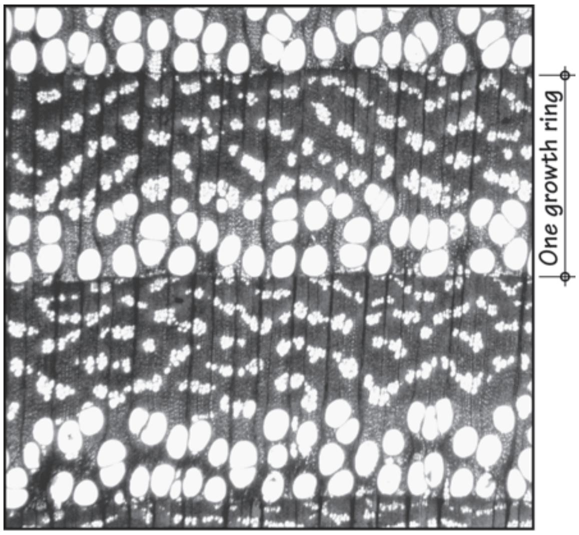

One growth ring

FIGURE 13.9 Magnified view of a hardwood's growth rings showing that it has a more complex microstructure than that of softwood. (Photo courtesy of the Forest Products Laboratory, U.S. Department of Agriculture)

For instance, a piece of lumber is much stronger along the grain (parallel to the axis of cells) than across the grain (perpendicular to the axis of cells), Figure 13.11. In fact, lumber's tensile strength across the grain is so small that it is neglected, as if the individual straws were not glued together. Thus, unlike steel and concrete, which are isotropic materials (having the same properties in all directions), wood is an anisotropic material.

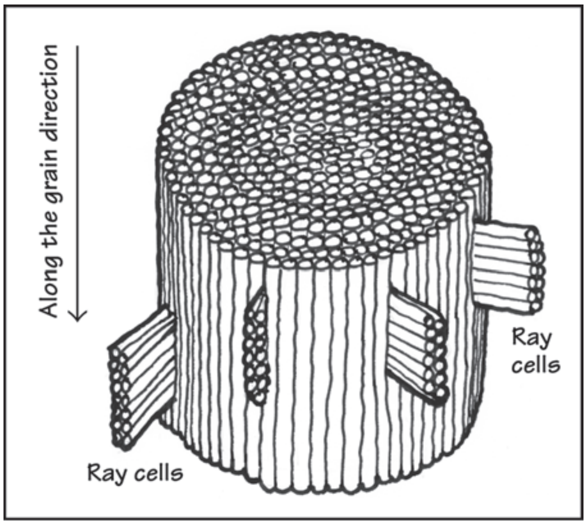


FIGURE 13.10 A highly simplified version of the cellular structure of wood—consisting mainly of hollow tubes oriented along the length of the member, resembling a bundle of straws glued together.

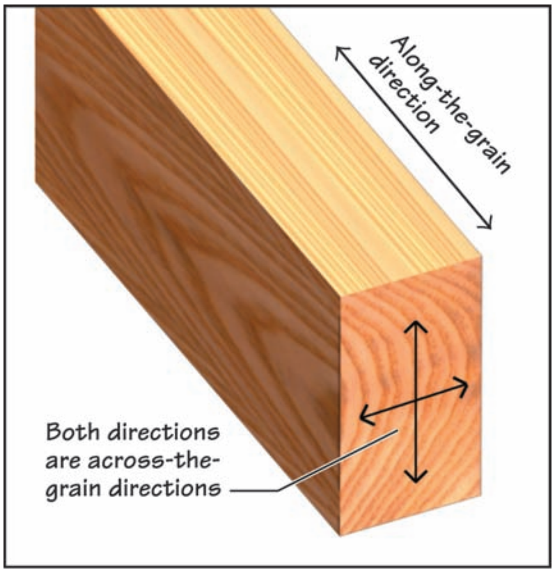

Along-the-grain direction
Both directions are across-the-grain directions

FIGURE 13.11 Along-the-grain and across-the-grain directions in lumber.

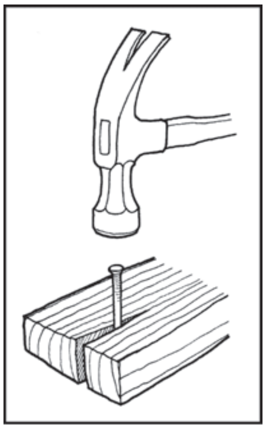


FIGURE 13.12 Lumber splits easily when nailed close to an end because of its low tensile strength across the grain resulting from the weak glue bond between fibers.

The weak glue bond between individual cells (drinking straws) explains why a lumber piece will easily split along the grain when nailed near an end, Figure 13.12. For the same reason, wood is weaker in shear along the grain than across the grain, because individual cells can easily slip (slide) against each other.

As we will see in Section 13.5, a piece of lumber shrinks substantially across the grain because the cell walls become thinner as water leaves them. However, along the grain (lengthwise), the departure of water has very little effect. Thus, lumber shrinks negligibly along the grain.

USES OF SOFTWOODS AND HARDWOODS

Softwood trees mature for harvesting two to three times faster than hardwood trees. Nearly 75% of North American forests contain softwoods. Because of their faster growth and, hence, their relative abundance, softwoods are commonly used for structural framing of wood buildings in North America. Thus, in most buildings, floor joists, rafters, ceiling joists, studs, sheathing, and so on, are of softwood lumber.

Hardwoods are commonly used for finish flooring, where their higher densities (giving greater abrasion resistance) are useful. Because hardwoods have a more interesting and varied grain structure, they are also used for wall paneling, trims, cabinets, furniture, and so on. Table 13.2 gives some of the major softwood and hardwood species used in building construction in North America.

TABLE 13.2 MAJOR SOFTWOOD AND HARDWOOD LUMBER SPECIES USED IN NORTH AMERICA

Softwood lumber		**Hardwood lumber**
Framing lumber (studs, floor and ceiling joists, rafters, headers, etc.) Southern pine, western lumber, north and northeastern lumber, and Canadian lumber (see Figure 13.11)	Roof shingles, fencing, etc. Decay-resistant woods such as redwood, western red cedar, white cedar, and southern cypress	Finish flooring Red oak and white oak are most common. Sugar maple, pecan, hickory, and teak are also used.
Siding, paneling, fascia boards, etc. Almost all species used for framing can be used for these nonstructural applications.	Finish flooring Denser species such as southern pine and douglas fir	Paneling and molding Ash, beech, hickory, red oak, white oak, sugar maple, pecan, black walnut, and teak
	Doors, windows, and cabinets Ponderosa pine, sugar pine, and Idaho white pine	

Each question has only one correct answer. Select the choice that best answers the question.

1. Which of the following two terms are used synonymously?
   a. *Lumber* and *wood*
   b. *Lumber* and *laminated veneer lumber*
   c. *Lumber* and *solid sawn lumber*
   d. All of the above

2. The approximate density of lumber is
   a. 35 pcf.
   b. 35 psf.
   c. 55 pcf.
   d. 55 psf.
   e. 75 pcf.

3. The cellular structure of wood consists mainly of
   a. hollow, small, approximately spherical cells.
   b. solid, small, approximately spherical cells.
   c. hollow, small, approximately ellipsoidal cells.
   d. hollow, long tubular cells.
   e. either (c) or (d).

4. If we cut a cross section through a tree trunk, we will see a number of rings. The most appropriate term for these rings is
   a. *annual rings*.
   b. *growth rings*.
   c. *concentric rings*.
   d. *eccentric rings*.
   e. all of the above.

5. The walls of wood cells consist primarily of
   a. calcium.
   b. glucose.
   c. cellulose.
   d. copper.
   e. lignin.

6. The terms *sapwood* and *heartwood* refer to
   a. two different wood species.
   b. two different subspecies of wood.
   c. two different types of wood cells.
   d. two different parts of a growth ring.
   e. two different parts of the same tree.

7. The difference between softwoods and hardwoods is based on the
   a. strength of wood.
   b. density of wood.
   c. abrasion resistance of wood.
   d. botanical characteristics.
   e. decay resistance of wood.

8. Which of the following species of wood is not a softwood?
   a. Pine
   b. Fir
   c. Cedar
   d. Oak
   e. Redwood

9. Which of the following species of wood is not a hardwood?
   a. Teak
   b. Balsa wood
   c. Rosewood
   d. Oak
   e. Redwood

10. Spruce is a softwood species.
   a. True
   b. False

11. Lumber used for structural framing of buildings in North America is generally derived
   a. from softwood species.
   b. from hardwood species.
   c. from both softwoods and hardwoods, depending on the price of lumber.
   d. from both softwoods and hardwoods, depending on the time of the year.

12. Hardwoods are generally used for fine-quality flooring, furniture, and wall paneling.
   a. True
   b. False

13. In the United States, most structural lumber is grown in the
   a. northern region of the United States.
   b. western and southern regions of the United States.
   c. eastern and northeastern regions of the United States.
   d. central region of the United States.
   e. none of the above, because most structural lumber is imported from Mexico.

14. Redwood is grown mainly in
   a. Texas.
   b. Florida.
   c. Oklahoma.
   d. Arizona.
   e. California.

15. Which of the following species of wood is naturally decay resistant?
   a. Pine
   b. Fir
   c. Spruce
   d. Cedar
   e. Hemlock

16. In a 2 × 6 stud, the wood grain is parallel to the
   a. vertical direction.
   b. 2-in. dimension.
   c. 6-in. dimension.

17. Wood is
   a. stronger along the grain than across the grain.
   b. stronger across the grain than along the grain.
   c. equally strong in both directions of the grain.

13.4 FROM LOGS TO FINISHED LUMBER

The conversion of logs into finished lumber takes place in lumber mills, which are usually located close to the forests. The conversion process consists of five basic steps:

- Transportation of logs from the forest to the mill, Figure 13.13.
- Storage of logs in the mill as raw material, Figure 13.14.
- Debarking of logs and sawing them into desired lengths, Figures 13.15 and 13.16.
- Sawing of logs into lumber of desired cross sections, Figure 13.17.
- Surfacing of lumber members smooth.

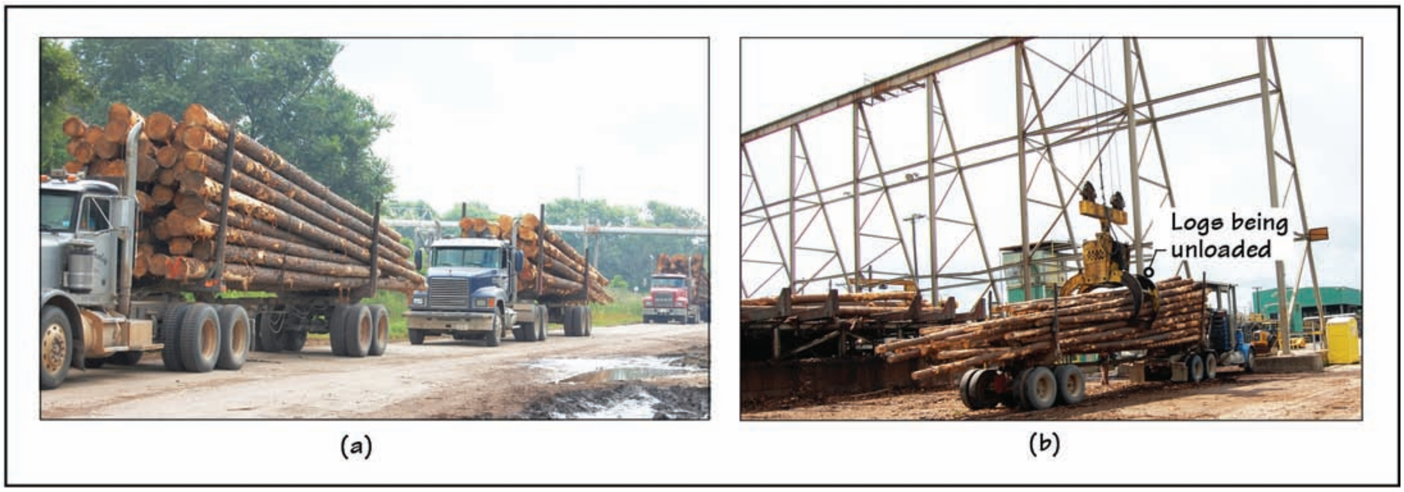

Logs being unloaded
(a)
(b)

FIGURE 13.13 **(a)** Logs leaving the forest for delivery to the lumber mill. **(b)** Logs being weighed and unloaded at entry to lumber mill.

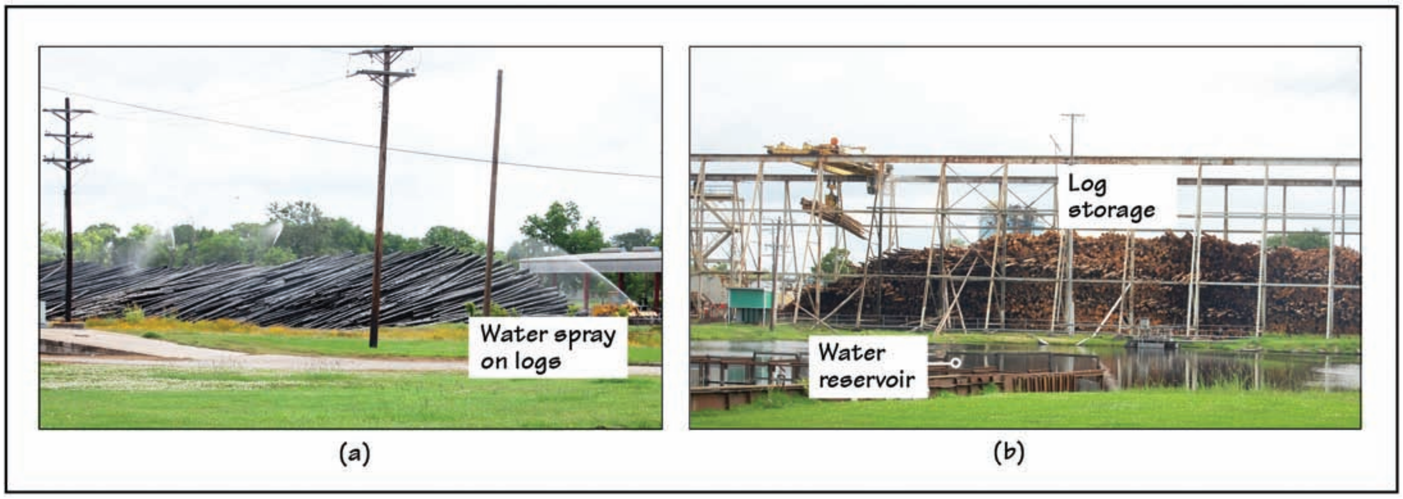

Water spray on logs
Log storage
Water reservoir
(a)
(b)

FIGURE 13.14 The logging operation is interrupted by rain and snow because forest roads are unpaved, dirt roads that become impassable during rain and snow. Therefore, logging operation is seasonal. However, mill operations must continue throughout the year. Consequently, lumber mills stock sufficient quantities of the raw material (logs) for uninterrupted manufacturing. **(a)** Because the logs develop checks and splits on drying and become brittle, they are kept moist by spraying water on them. **(b)** An important feature of a lumber mill is a water reservoir located close to the log storage area.

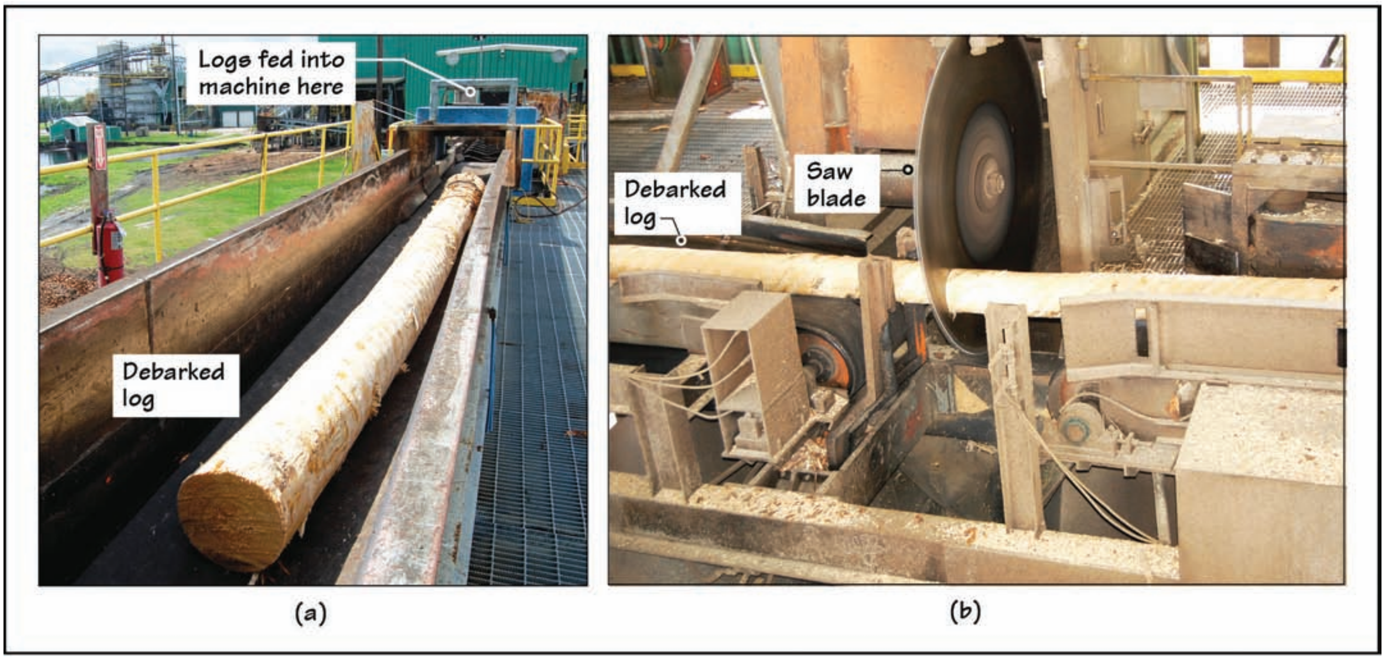

Logs fed into machine here
Debarked log
Debarked log
Saw blade
(a)
(b)

FIGURE 13.15 **(a)** The first operation in the manufacturing of lumber members is the debarking of logs. In this machine the logs are fed from the far end and the debarked logs appear at the near end. Some mills use the bark as energy source for manufacturing. **(b)** The debarked logs are sawn into desired lengths.

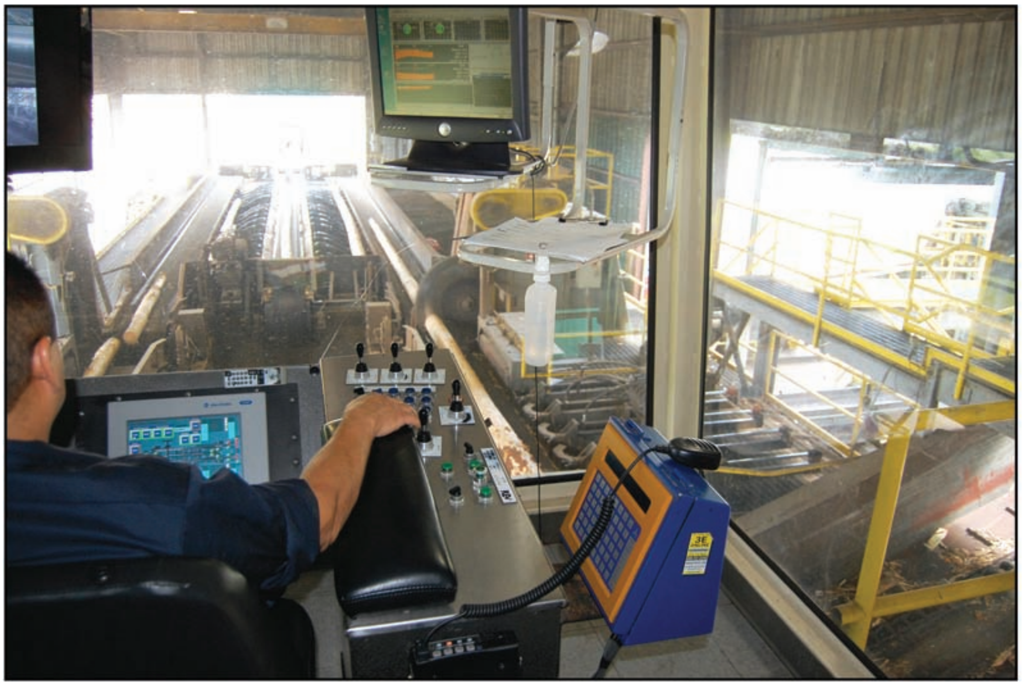


FIGURE 13.16 The manufacturing of lumber is fully computerized and uses only a small pool of skilled workforce. This image shows the control room for log debarking and sawing operations. The room is located at vantage height to give a clear view of all operations to the technician.

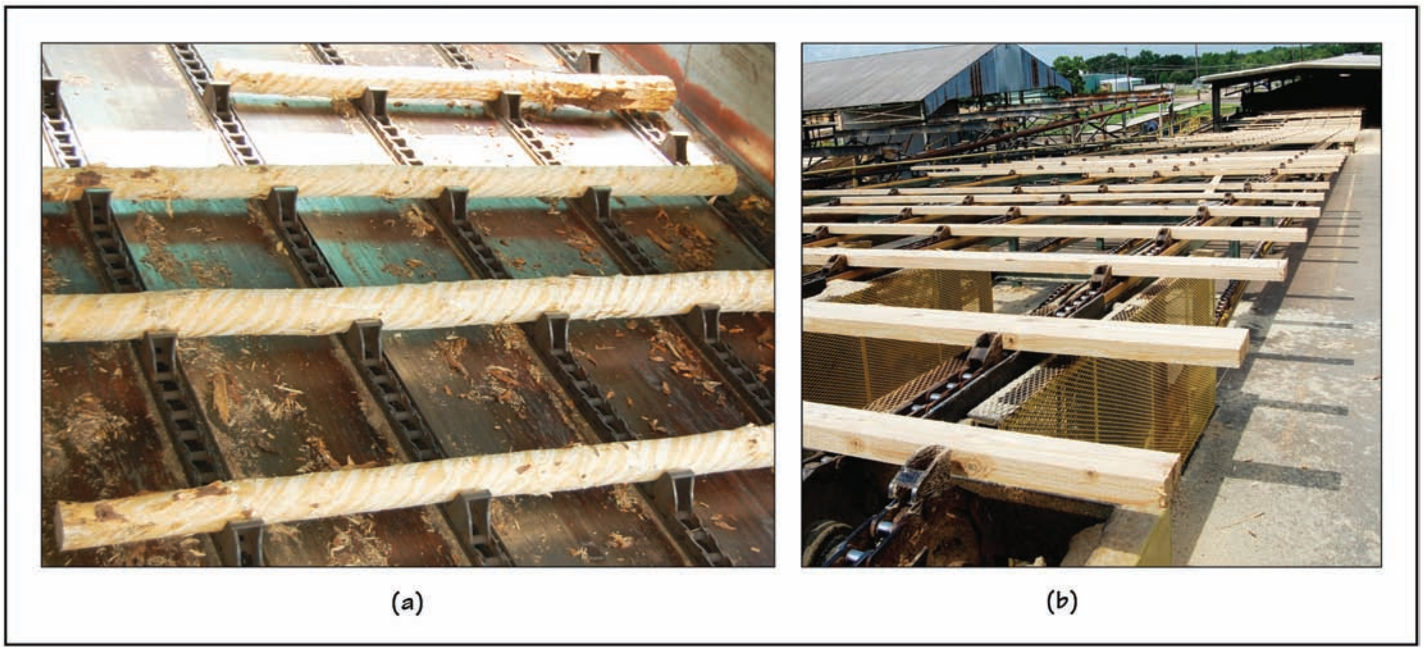


FIGURE 13.17 **(a)** Logs sawn into desired lengths travel down a sloped platform for conversion into rectangular cross sections. **(b)** The rectangular cross sections travel for drying (Section 13.5) and surfacing (Section 13.6). Note that the cross sections are rough at this stage.

In a modern mill, the conversion of logs to lumber is highly automated and is controlled through one or more control rooms depending on the mill's manufacturing sophistication. A control room is equipped with computer monitors to help the technician determine the most marketable quantity of wood from a log, as shown in Figure 13.16. The control room is located at an elevation that allows the technician to physically observe the operation.

FLAT-SAWN AND RADIAL-SAWN LUMBER

Two methods are commonly used for sawing the logs: *flat sawing* and *radial sawing*. The lumber pieces so obtained are referred to as *flat-sawn lumber* and *radial-sawn lumber*, respectively.

In flat-sawn lumber, the growth rings in some pieces run parallel to the edges of the cross section. In other pieces, the rings are diagonally oriented to the edges, and in a few other pieces, the rings are perpendicular, Figure 13.18. Another term used for flat sawing is *plain sawing*.

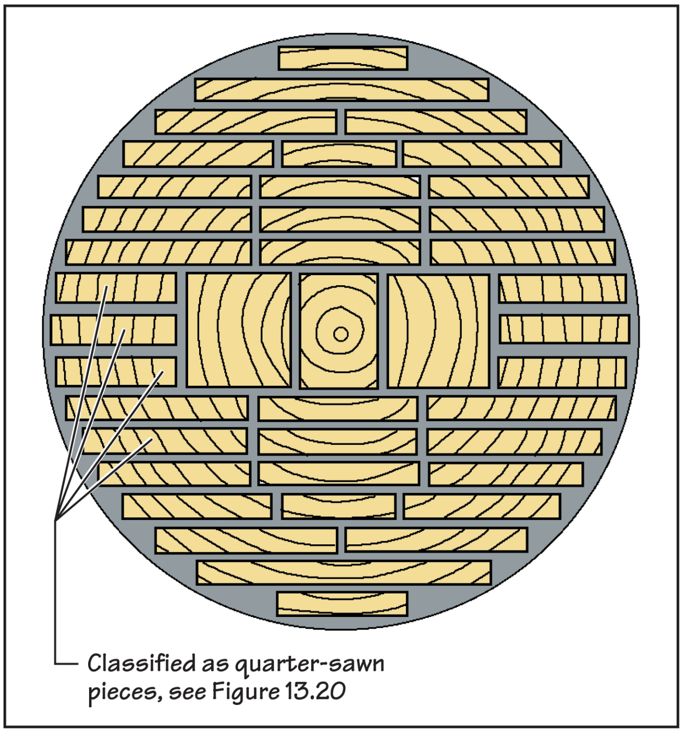

Classified as quarter-sawn pieces, see Figure 13.20

FIGURE 13.18 Flat sawing of a large-diameter log in two directions yields several pieces of dimension lumber and timbers. In a small-diameter log, the sawing may be in one direction only (through-and-through sawing), giving primarily dimension lumber. (See Section 13.9 for the definition of the term dimension lumber.)

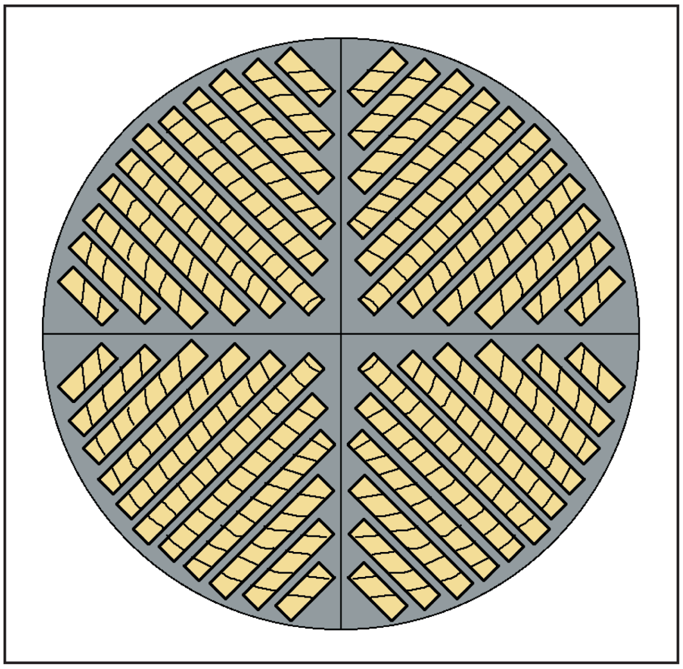


FIGURE 13.19 Quarter (radial) sawing of a log. Note that in comparison with flat sawing, radial sawing is more wasteful of wood.

In radial sawing, the log is first converted into four pieces through the center of the log. That is why the term *quarter sawing* is used interchangeably with *radial sawing*. Each quarter is then sawed radially into the required sizes, Figure 13.19. In a quarter-sawn piece, obtained from the log's center, the growth rings are perpendicular to its wider faces.

In a radial-sawn piece farther from the log's center, the angle between the rings and the wider faces of the cross section is less than 90°. Some lumber experts define a quarter-sawn piece as the one whose growth rings make an angle of 45° or more with the wider face of its cross section, Figure 13.20 (even if the piece has been obtained from flat sawing). Thus, some of the pieces in Figure 13.18 are classified as quarter-sawn. If the angle is less than 45°, the piece is classified as flat-sawn.

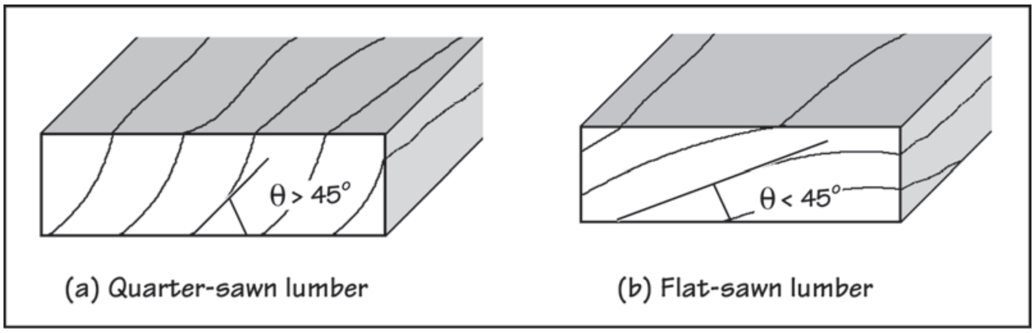

θ > 45°
(a) Quarter-sawn lumber
θ < 45°
(b) Flat-sawn lumber

FIGURE 13.20 Theoretical definitions of quarter-sawn and flat-sawn lumber members.

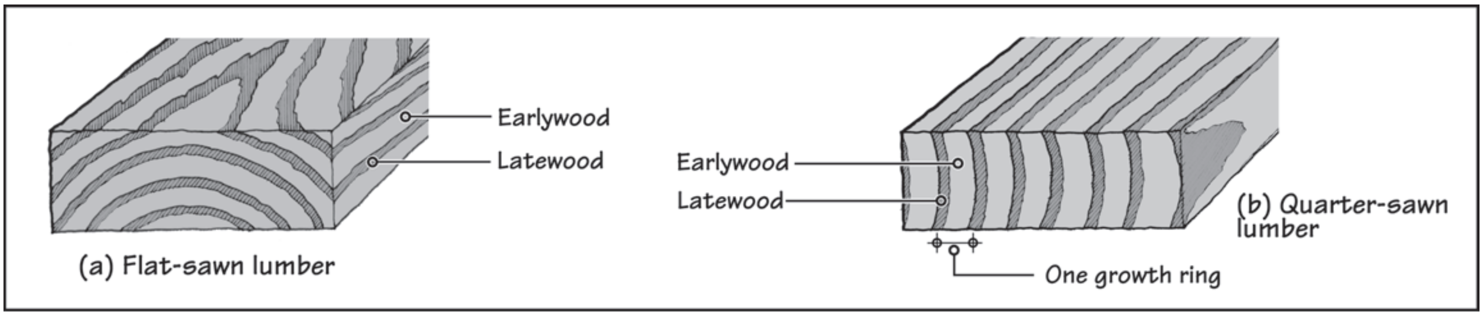

Earlywood
Latewood
(a) Flat-sawn lumber
Earlywood
Latewood
(b) Quarter-sawn lumber
One growth ring

FIGURE 13.21 The distribution of denser latewood and lighter earlywood in quarter-sawn lumber is more even than in flat-sawn lumber.

Quarter sawing is more complex and usually more wasteful. Hence, most framing lumber is obtained by flat sawing. As we will see later in this section, quarter-sawn lumber is more dimensionally stable. It resists wear and abrasion more evenly because denser latewood is more uniformly exposed on the surfaces of the lumber piece, Figure 13.21. Quarter-sawn lumber is commonly specified for high-grade finish floors.

13.5 DRYING OF LUMBER

After sawing, the lumber is dried and subsequently surfaced smooth before being shipped to lumber yards for sale. Although the drying of wood begins from the time the tree is cut and converted to logs, the moisture content prior to sawing far exceeds that required for use in buildings. Therefore, lumber must be dried (or seasoned). The term *seasoning* implies a controlled rate of drying. Controlled drying minimizes the separation of fibers that occurs during the drying process.

The moisture content (MC) in a piece of wood is the weight of water in the wood divided by its oven-dry (completely dry) weight, expressed as a percentage:

$$\text{MC} = \frac{\text{weight of water in wood}}{\text{weight of oven-dry wood}} \times 100$$

Let us assume that a piece of wood weighs 6 lb. Now let us dry it until all of its water has evaporated and then weigh it again. If the weight of this dry piece is 4.5 lb (implying that the weight of water in the wood was 1.5 lb), the moisture content in the wood before drying, as obtained from the preceding equation, is

$$\text{MC} = \frac{1.5}{4.5} \times 100 = 33.3\%$$

The moisture content in the tree before it is cut varies with the species and may be as high as 200%. Some of this water is contained in cell walls, which are in their fully swollen state, and some of the water is contained in cell cavities. During the drying process, the cavity water, referred to as *free water*, evaporates first.

After all the free water has evaporated, the cell wall water, called the *bound water*, begins to evaporate, Figure 13.22. The stage at which all the free water has evaporated and the bound water has just begun to evaporate is referred to as the *fiber saturation point* (FSP). At this point, the cell walls are in their fully swollen state, just as they were when there was free water in the cells.

Green versus Dry Lumber

The average moisture content in lumber at the FSP is approximately 30%. It is only when the moisture content in wood falls below FSP (i.e., when the bound water begins to evaporate) that the water leaves the cell walls and the wood begins to shrink. No shrinkage of wood occurs if its moisture content is greater than its fiber saturation point. Dimensional changes in lumber (shrinkage and swelling) are discussed later in this section.

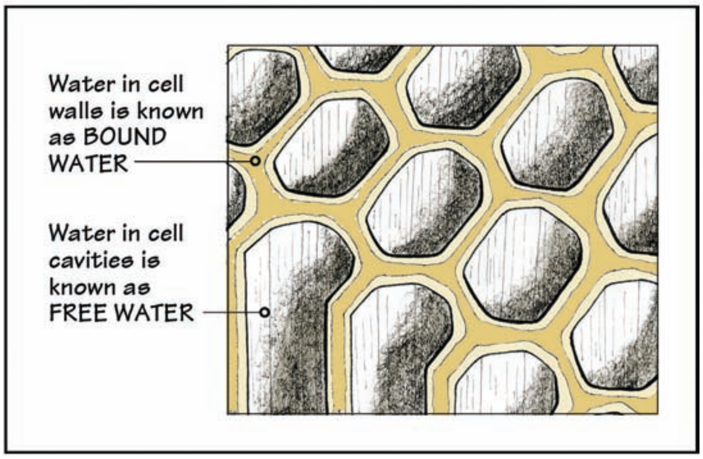

Water in cell walls is known as BOUND WATER
Water in cell cavities is known as FREE WATER

FIGURE 13.22 Free water and bound water in lumber cross sections.

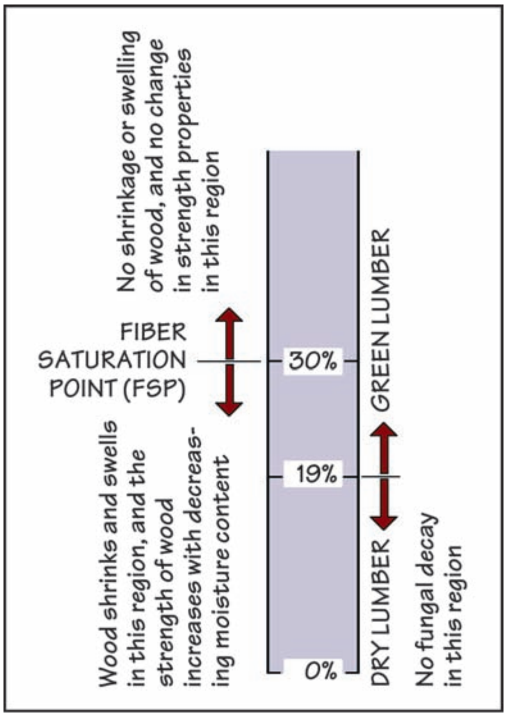

No shrinkage or swelling of wood, and no change in strength properties in this region
FIBER SATURATION POINT (FSP)
30%
GREEN LUMBER
19%
Wood shrinks and swells in this region, and the strength of wood increases with decreasing moisture content
0%
DRY LUMBER
No fungal decay in this region

FIGURE 13.23 Definitions of dry lumber and green lumber as a function of lumber's moisture content.

Lumber is typically seasoned in the mill to a moisture content of 19% or less—a value that distinguishes *dry* lumber from *green* lumber. Thus, a piece of lumber whose moisture content is less than or equal to 19% is referred to as *dry lumber*, and that whose moisture content is 20% or greater is referred to as *green lumber*, Figure 13.23.

The value of 19% has been selected because lumber with a moisture content of 19% or less is not susceptible to fungal decay. Additionally, the strength properties of lumber do not improve significantly below 19% moisture content. Note that the strength and stiffness of lumber increase as the moisture content decreases beyond the fiber saturation point. Seasoning also helps to reduce transportation costs because a drier piece of lumber weighs less.

AIR SEASONING VERSUS KILN SEASONING

Two processes are used to season lumber: *air seasoning* and *kiln seasoning*. In air seasoning, lumber pieces dry naturally. They are simply stacked one over the other in piles in such a way that air can circulate freely around them. The piles are kept under a roof to prevent the direct action of rain, snow, or sun.

Air seasoning is a slow process that can take several months, depending on the thicknesses and species of lumber. Kiln seasoning is much faster. The high temperature in the kiln also kills any fungus that may be present in the living tree. In kiln seasoning, the lumber is stacked in a chamber through which warm air with a controlled amount of humidity (steam) is circulated. Figure 13.24 shows a typical seasoning kiln.

A piece of lumber (air or kiln) seasoned to a moisture content of 19% or less is identified as *surfaced dry* (S-DRY). If the moisture content at the time of surfacing is more than 19%, the lumber is identified as *surfaced green* (S-GRN). Some mills season lumber to a moisture content of 15% or less. The identification in that case is MC 15 or KD 15; KD stands for *kiln dried*. As we will see in Section 13.11, the identification of its moisture content is an important component of the lumber grade.

Lumbers marked S-DRY, MC 15, or KD 15 are considered to be equivalent for most structural purposes. However, for nonstructural uses, such as for wall and ceiling paneling and flooring, where greater dimensional stability is needed, a lower moisture content is desirable. Additionally, it is generally immaterial whether lumber is kiln or air dried.

SHRINKAGE AND SWELLING OF LUMBER

As stated previously, wood begins to shrink only when the water from cell walls begins to evaporate, that is, when the moisture content in wood is less than the fiber saturation point. The drying shrinkage of cell walls affects the dimensions of lumber's cross section only, not its length. Consequently, a vertical lumber member, such as a stud, shortens negligibly along

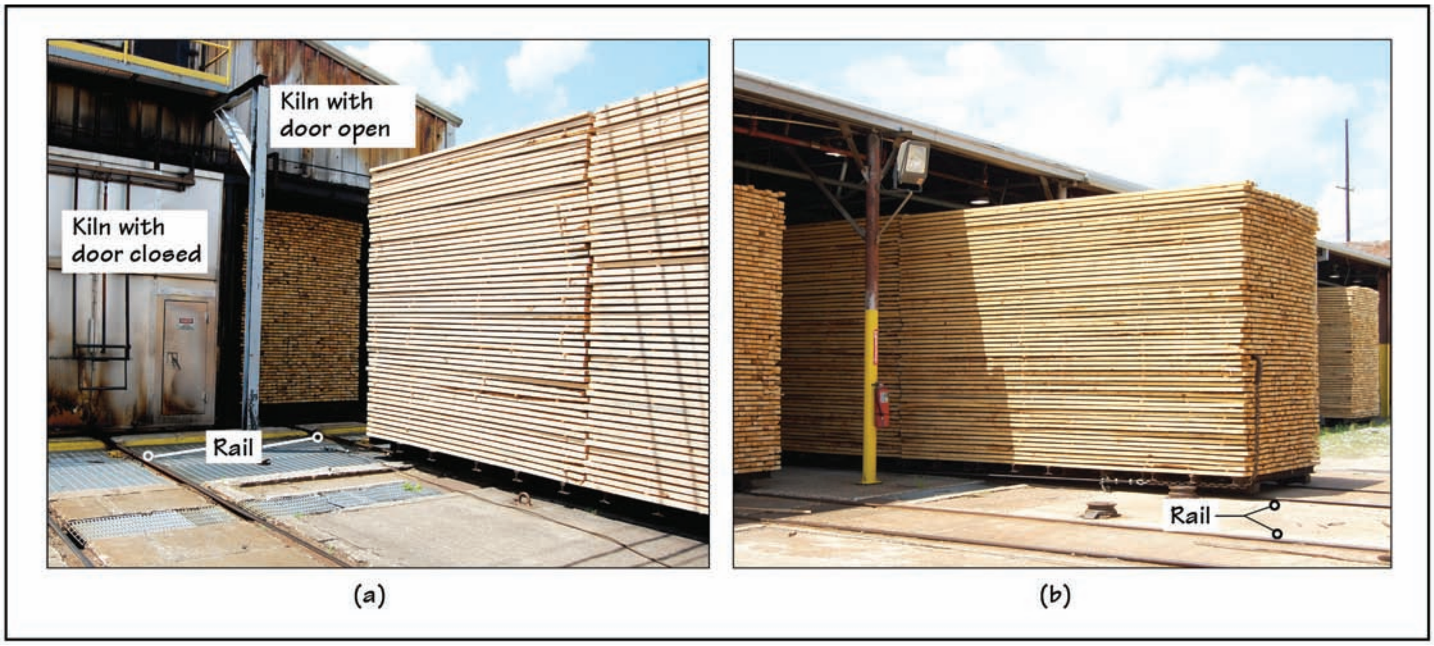
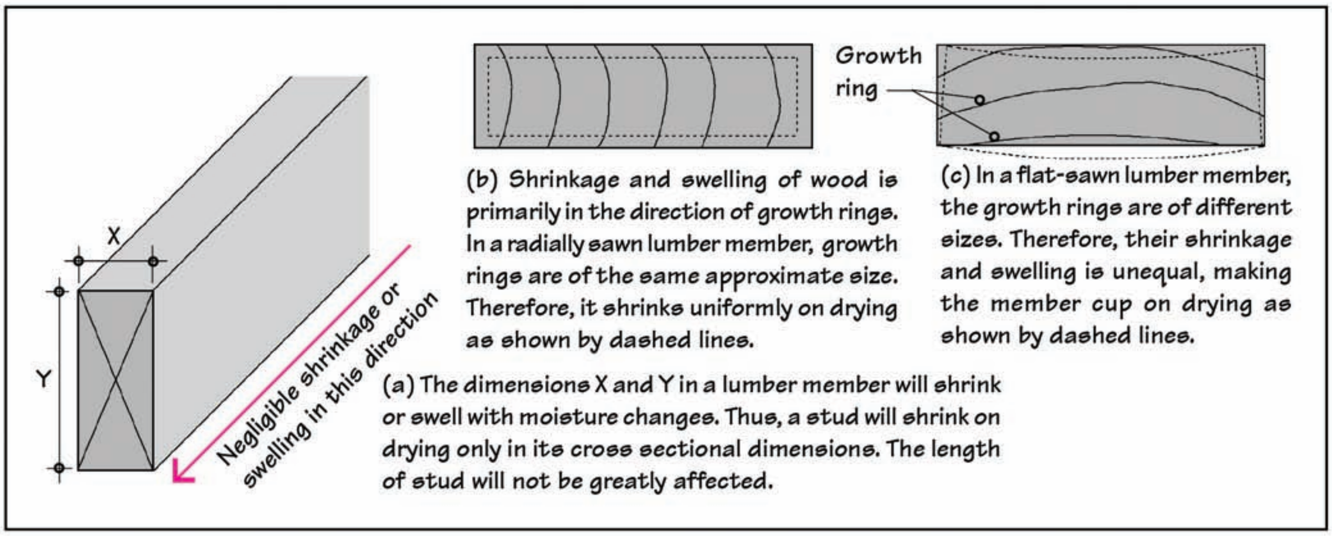


FIGURE 13.24 **(a)** Stacks of unseasoned lumber supported on rails wait outside the kiln to move inside for seasoning. The kiln's open door indicates that the stack inside the kiln has been seasoned and is slowly traveling out of it from the opposite door to make way for the new, unseasoned stack. **(b)** A lumber storage yard is located close to the exit door of the kiln to which the stack travels on rails for storage until taken for surfacing of lumber members.



(b) Shrinkage and swelling of wood is primarily in the direction of growth rings. In a radially sawn lumber member, growth rings are of the same approximate size. Therefore, it shrinks uniformly on drying as shown by dashed lines.

(c) In a flat-sawn lumber member, the growth rings are of different sizes. Therefore, their shrinkage and swelling is unequal, making the member cup on drying as shown by dashed lines.

(a) The dimensions X and Y in a lumber member will shrink or swell with moisture changes. Thus, a stud will shrink on drying only in its cross sectional dimensions. The length of stud will not be greatly affected.

FIGURE 13.25 Drying shrinkage of a lumber member.

its height on drying. Similarly, the shrinkage of a floor joist is negligible along its length. In other words, wood shrinks only across the grain, not along the grain, Figure 13.25(a).

Cell walls not only shrink on drying but also expand when their moisture content increases. Being hygroscopic, cell walls respond to the water vapor in air. Therefore, a lumber cross section will generally shrink and swell due to the changes in the relative humidity of air. The shrinkage and swelling are much larger along the direction of growth rings in lumber (tangential direction) than perpendicular to the direction of growth rings (radial direction).

Consequently, quarter-sawn lumber shrinks uniformly, Figure 13.25(b) and tangentially (flat-) sawn lumber will generally cup, bow, or twist on drying, Figure 13.25(c). This is another reason why radially sawn lumber is preferred for wood flooring.

NOTE

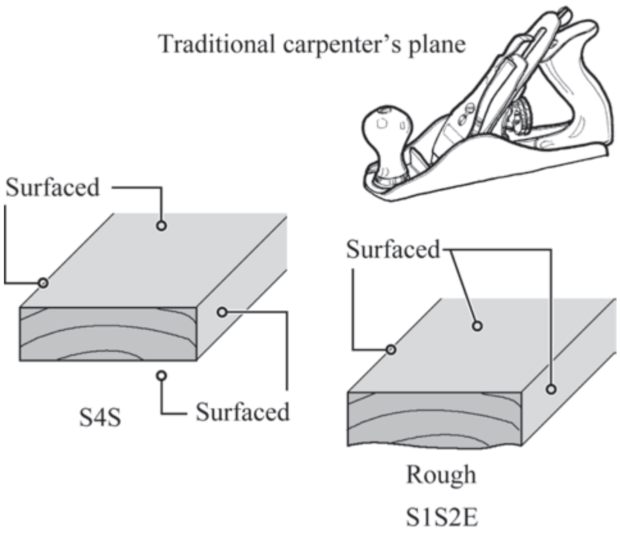
S-DRY, MC 15, and KD 15 are considered equivalent moisture-content designations for framing lumber. However, sawn lumber used in glulam beams and wood I-joists is generally seasoned to a moisture content of less than or equal to 15%.

13.6 LUMBER SURFACING

Saw blades used for mass manufacturing are coarse-edged. Therefore, lumber obtained after sawing is quite rough. Because rough surfaces can cause injuries to framers, lumber used in conventional wood light framing is surfaced smooth.

Surfacing is done by high-speed planing machines—a replacement for the traditional hand-held carpenter's plane. Surfacing smooths lumber, rounds off the edges, and makes it more square, removing some of the distortions that have occurred during the seasoning process. That is why seasoning usually precedes surfacing. Lumber that has been surfaced before seasoning is identified as S-GRN (surfaced green).

Framing lumber is surfaced on its longitudinal faces, not the ends, because the ends are usually resawn during construction. A piece surfaced on one wide face only is referred to as *S1S* (surfaced on one side); if surfaced on both wide faces, it is called *S2S* (surfaced on two sides); if surfaced on all four faces, it is called *S4S*.



EXPAND YOUR KNOWLEDGE

Moisture Content of Wood and Relative Humidity of Air

A piece of lumber swells and shrinks with changes in the relative humidity (RH) of the surrounding air and gradually reaches an equilibrium moisture content (EMC). Although the relationship of EMC with RH varies somewhat with the species, the following represents a good average.

Based on this relationship, the average moisture content in framing lumber lies between 5% and 14%, depending on how arid or humid the location is.

RH	EMC	RH	EMC
0%	0%	75%	14%
25%	4.5%	90%	20%
50%	8.5%	100%	FSP approx. 30%

Source: Bruce Hadley. *Understanding Wood*. Newtown, CT: Taunton Press, 1980, p. 69.

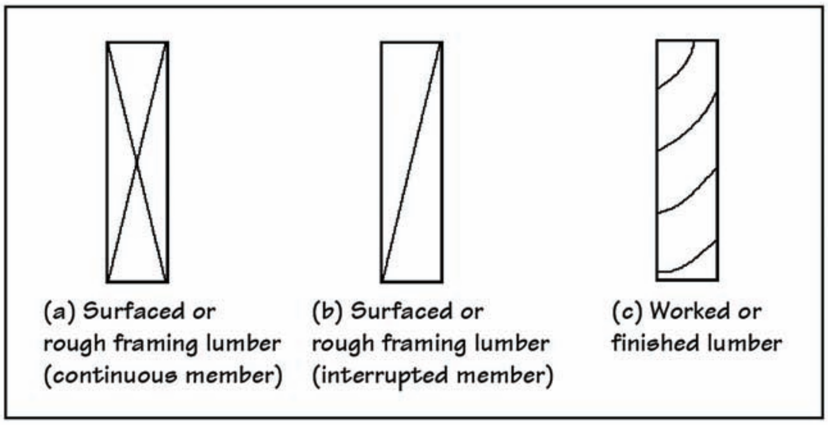

(a) Surfaced or rough framing lumber (continuous member)
(b) Surfaced or rough framing lumber (interrupted member)
(c) Worked or finished lumber

FIGURE 13.26 Graphic symbols for framing lumber and worked (finished) lumber.

A piece that is surfaced on one wide face and one narrow face (edge) is called *S1S1E* (surfaced on one side and one edge). Other designations are *S2S1E* and *S1S2E*. Lumber used for structural framing is typically surfaced S4S, fascia boards, as S1S2E, and so on.

In construction drawings, rough or surfaced lumber is graphically depicted by diagonal lines through its cross section. Two crossed diagonal lines indicate a continuous member, Figure 13.26(a), and one diagonal line indicates an interrupted (discontinuous) member, such as blocking or shims, Figure 13.26(b). Surfaced lumber is used for framing members, which are typically covered over by finish materials such as gypsum wallboard or plywood subflooring. Rough lumber is used for exposed lumber components (unprotected by gypsum board, etc.), particularly for beams and columns of large cross sections.

A *worked (finished) lumber* member is represented by growth ring symbols in the cross section, Figure 13.26(c). Worked lumber is lumber that has been dressed by additional machining to obtain the required profile. Worked lumber is used for interior finish members, such as door and window frames, trims and moldings, finish flooring, paneling, and so on. Figure 13.27 shows a typical section through the head of a door, illustrating the use of lumber's graphic symbols.

FINGER-JOINTED LUMBER

Two lumber pieces can be glued together to produce a longer member using complementary finger joints on either side, Figure 13.28. By finger jointing, defects in a wood member are cut away and the good pieces are joined to obtain higher-grade lumber.

Because of high-strength and water-resistant glues, a finger-jointed member is as strong as a single-length (unjointed) member. Jointed and unjointed members can be used interchangeably in vertical applications only (that is, as stud members). They are not allowed in bending members (joists or rafters).

13.7 NOMINAL AND ACTUAL DIMENSIONS OF LUMBER

In North America, a softwood lumber's cross section is specified by its nominal dimensions rather than by its actual dimensions. Thus, when we say that a lumber piece is 2 × 4 (two by four), we refer to its nominal dimensions and imply that its cross section measures 2 in. × 4 in. nominally. The actual dimensions of a 2 × 4 (surfaced dry) are $1\frac{1}{2}$ in. × $3\frac{1}{2}$ in.

In stating the nominal dimensions, the inch label is not used. For the actual dimensions, however, inch labels must be used. Thus, the size with and without the inch labels distinguishes the actual size from the nominal size.

Nominal dimensions correspond roughly to the wood in the log before it is sawn, seasoned, and surfaced. The difference between the two represents the amount of wood lost due to shrinkage, sawing, and surfacing. The relationship between the nominal and actual dimensions of S-DRY lumber is shown in Table 13.3. Thus, a 2 × 10 (two by ten) dry lumber cross section actually measures $1\frac{1}{2}$ in. × $9\frac{1}{4}$ in.

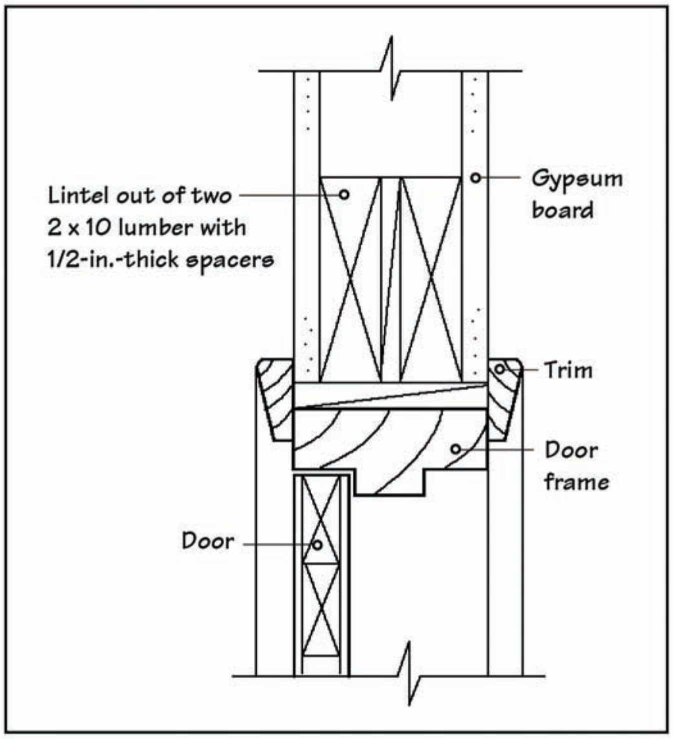


FIGURE 13.27 A section through the head of a door illustrating the use of graphic symbols for lumber members.

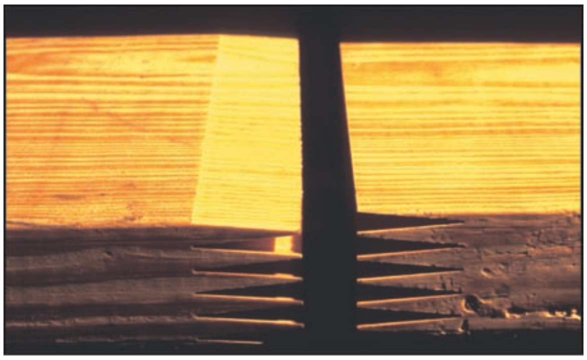


FIGURE 13.28 Finger jointing of lumber pieces.

Although the stated actual dimensions are reasonably accurate for construction purposes, wood cross sections do not have the same dimensional precision as steel cross sections, because wood swells and shrinks with changes in relative humidity in the atmosphere.

13.8 BOARD FOOT MEASURE

In the United States, softwood lumber is sold by volume, similar to concrete.* The obvious volumetric measure is the cubic foot (or cubic yard; in the SI system, it is a cubic meter). However, a volumetric measure that is unique to lumber is the *board foot* (bd ft). One board foot is the amount of lumber contained in a 1-in.-thick board that measures 1 ft × 1 ft on its face. In other words, 1 $\text{ft}^3 = 12$ bd ft.

Thus, a 2 × 12 piece of lumber that is 20 ft long contains 40 bd ft. One hundred such pieces contain 4,000 bd ft. In calculating board feet, we use the nominal dimensions, not the actual dimensions, of lumber.

The price of lumber is quoted in terms of 1,000 bd ft (MBF) and varies according to the lumber's cross-sectional dimensions and grade. Larger cross sections, longer lengths, and higher grades cost more. In a home-improvement building material store, lumber is typically sold per piece rather than by the board foot. In Europe and other countries, where the SI system prevails, lumber is sold by the cubic meter.

TABLE 13.3 NOMINAL AND ACTUAL SIZES OF S-DRY LUMBER

Nominal size	Actual size
1	$\frac{3}{4}$ in.
$1\frac{1}{2}$	$1\frac{1}{4}$ in.
2	$1\frac{1}{2}$ in.
3	$2\frac{1}{2}$ in.
4	$3\frac{1}{2}$ in.
5	$4\frac{1}{2}$ in.
6	$5\frac{1}{2}$ in.
8	$7\frac{1}{4}$ in.
10	$9\frac{1}{4}$ in.
12	$11\frac{1}{4}$ in.
14	$13\frac{1}{4}$ in.

Example

Determine how much a builder will pay a lumber wholesaler for 900 pieces of 2 × 12 lumber, each 16 ft long. The price of lumber is $800 per MBF.

Solution

$$\text{Total volume of lumber} = \frac{(16 \times 2 \times 12)(900)}{(12 \times 12)} = 2{,}400\ \text{ft}^3 = 2{,}400(12)\text{bd ft} = 28.8\ \text{MBF}$$

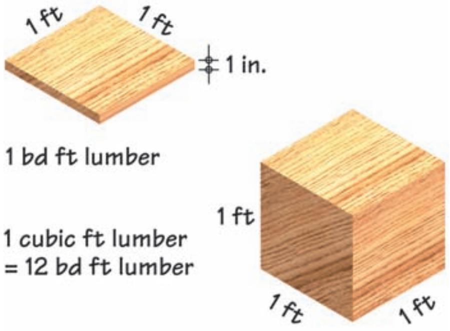
$$\text{Total price of lumber} = 28.8(800) = \$23{,}040$$

13.9 SOFTWOOD LUMBER CLASSIFICATION

A lumber piece is classified into one of the following three categories, Figure 13.29:

- Board lumber, or simply boards
- Dimension lumber
- Timbers

The distinction between them is based on the thickness of the member—thickness being the smaller of the two dimensions of its cross section. Thus, the thickness of a 4 × 10 member is 4 in. (nominal).



PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

18. Structural lumber is typically
  a. flat-sawn.
  b. quarter-sawn.
  c. either (a) or (b), depending on the type of structural member.

19. Flat-sawn lumber is dimensionally more stable than quarter-sawn lumber.
  a. True **b.** False

20. Which of the following terms means the same as quarter-sawn?
  a. Tangentially sawn **b.** Radially sawn

21. The weight of a piece of lumber is 2 lb. The weight of the same piece after it is fully dried is 1.8 lb. What was the original moisture content in the wood?
  a. 7% **b.** 9%
  c. 11% **d.** 15%
  e. None of the above

22. Fungal decay in wood occurs when the moisture content in wood is
  a. greater than or equal to 15%.
  b. greater than or equal to 20%.
  c. greater than or equal to 25%.
  d. between 15% and 25%.
  e. none of the above.

(*Continued*)

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*Concrete is sold per cubic yard of green (wet) concrete.

23. The moisture content in a piece of lumber has been measured to be 15%. According to the wood industry, this piece of lumber will be classified as
- **a.** dry.
- **b.** green.
- **c.** wet.
- **d.** moist.
- **e.** arid.

24. From the user's view point, the difference between MC 15 and KD 15 is generally ignored.
- **a.** True
- **b.** False

25. The term S-DRY implies that the lumber has been
- **a.** stored in a dry climate.
- **b.** sawed when its moisture content was ≤25%.
- **c.** surfaced when its moisture content was ≤25%.
- **d.** sawed when its moisture content was ≤19%.
- **e.** surfaced when its moisture content was ≤19%.

26. The term S2S implies that the lumber has been
- **a.** sawed twice.
- **b.** sawed from two sides.
- **c.** surfaced on two sides.
- **d.** none of the above.

27. A 10-ft-long stud was installed in position when the wood's moisture content was 19%. During a long dry spell, the wood's moisture content became 8%. The new stud length will be
- **a.** approximately 9 ft 10 in.
- **b.** approximately 9 ft $10\frac{1}{2}$ in.
- **c.** approximately 9 ft 11 in.
- **d.** approximately the same as the initial stud length of 10 ft.
- **e.** none of the above.

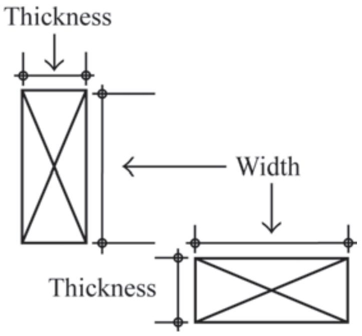
28. A piece of lumber has been specified as 2 in. × 4 in. in cross section. This refers to its
- **a.** actual cross-sectional dimensions.
- **b.** nominal cross-sectional dimensions.

29. The actual dimensions of 4 × 8 lumber are
- **a.** $3\frac{1}{2}$ in. × $7\frac{1}{2}$ in.
- **b.** $3\frac{1}{4}$ in. × $7\frac{1}{2}$ in.
- **c.** $3\frac{1}{4}$ in. × $7\frac{1}{4}$ in.
- **d.** $3\frac{1}{2}$ in. × $7\frac{1}{4}$ in.
- **e.** none of the above.

30. The actual dimensions of 2 × 12 lumber are
- **a.** $1\frac{1}{2}$ in. × 11 in.
- **b.** $1\frac{1}{2}$ in. × $11\frac{1}{2}$ in.
- **c.** $1\frac{1}{2}$ in. × $11\frac{3}{4}$ in.
- **d.** $1\frac{3}{4}$ in. × $11\frac{3}{4}$ in.
- **e.** none of the above.

31. In calculating the board foot measure, we must use the actual dimensions of lumber, not its nominal dimensions.
- **a.** True
- **b.** False

32. A retailer of building materials purchased 1,000 pieces of 2 × 12 lumber, each 10 ft long. How many board feet did the retailer purchase?
- **a.** 1,000 bd ft
- **b.** 10 MBF
- **c.** 20,000 bd ft
- **d.** 100,000 bd ft
- **e.** None of the above



The smaller cross-sectional dimension of a lumber member is its thickness, and the larger dimension is its width.

Board lumber includes lumber whose thickness is less than 2 in. nominal. Thus, 1 × 4, 1 × 12, $1\frac{1}{2}$ × 6, and so on, are boards. Usually, 16 in. (nominal) is the maximum available width in board lumber. Board lumber is used in nonstructural applications such as sheathing, fencing, and shelving.

Dimension lumber includes lumber whose (nominal) thickness is 2 in. to 4 in. The width of dimension lumber varies from 2 in. to 14 in. in steps of 2 in.—that is, 2 in., 4 in., 6 in., 8 in., and so on.* Thus, a 2 × 10, 3 × 6, 4 × 4, 4 × 8, 4 × 12, and so on, are all in the dimension lumber category.

Timbers includes lumber whose nominal thickness is 5 in. or greater. Thus, 5 × 8, 6 × 6, and 8 × 10 are timbers. Dimension lumber and timbers are graded based on their strength.

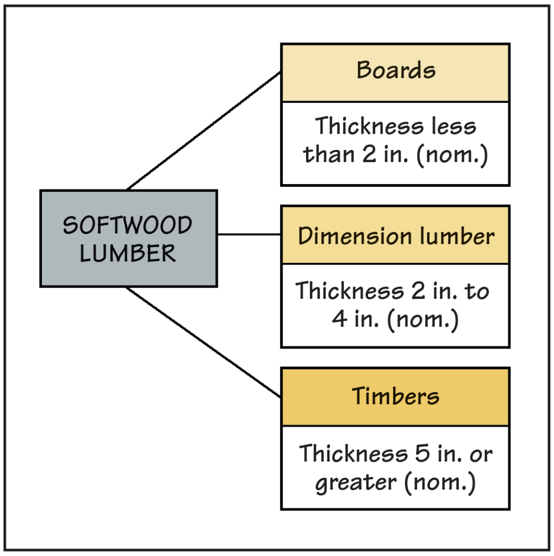
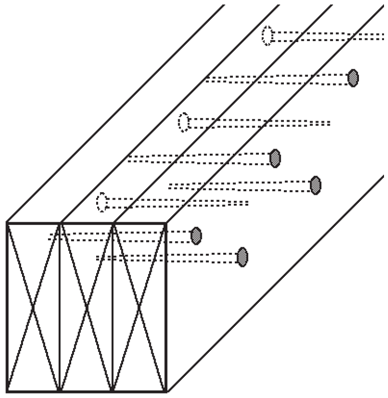

SOFTWOOD LUMBER
Boards
Thickness less than 2 in. (nom.)
Dimension lumber
Thickness 2 in. to 4 in. (nom.)
Timbers
Thickness 5 in. or greater (nom.)

FIGURE 13.29 Size-based softwood lumber classification.



Two or three 2-by lumber members may be nailed, screwed, or bolted together to obtain a thicker member.

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*A width greater than 12 in. may not be available in most lumber yards.

DIMENSION LUMBER AND TIMBERS

Most of the lumber used in structural framing of wood buildings is dimension lumber. Out of this, the 2 × (referred to as *two-by* or *2-by*) lumber is most commonly used. In fact, a whole house or an apartment block can be framed, for all practical purposes, using 2-by lumber only, such as 2 × 4, 2 × 6, 2 × 8, 2 × 10, and 2 × 12. If a member thicker than 2 in. is required, two or three 2-by members can be nailed, screwed, or bolted together.

Dimension lumber is available in lengths of 8 ft, 10 ft, 12 ft, and so on, in steps of 2 ft up to 28 ft. Most lumber yards do not regularly stock lumber longer than 20 ft. Local availability should be checked before specifying a certain length.

Two-by lumber is typically available as S4S and in surfaced dry condition. Three- or 4-in.-thick dimension lumber is available in dry or green condition. Timbers (5 in. and thicker) are generally shipped in green condition and are manufactured in S4S or rough condition.

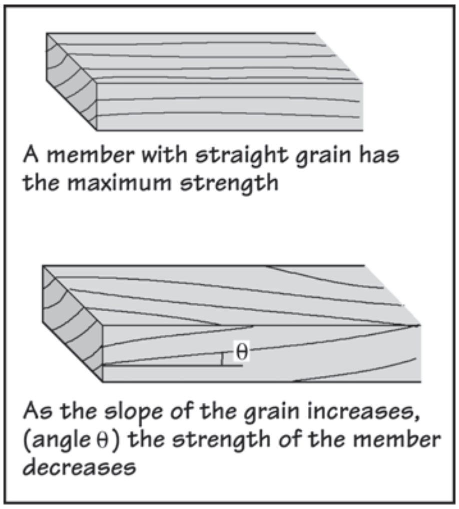

A member with straight grain has the maximum strength
θ
As the slope of the grain increases, (angle θ) the strength of the member decreases

FIGURE 13.30 The slope of the grain affects the lumber's strength. It is most easily observed by examining the longitudinal grain of the lumber in comparison with the edge of the member.

13.10 LUMBER'S STRENGTH AND APPEARANCE

As a naturally grown material, wood does not have the same degree of uniformity as steel or concrete. Although two steel beams of the same length and cross section have identical load-carrying capacities, this is not so with lumber beams. Thus, two lumber beams of the same length and cross-sectional dimensions, even obtained from the same log, can have vastly different load-carrying capacities.

As previously discussed, the strength of a piece of lumber is affected by its species and is a function of specific gravity. Strength is also affected by its growth and manufacturing characteristics. These include slope of grain, knots, checks, shakes, splits, and wane.

SLOPE OF GRAIN

An important factor that affects the strength of lumber is the slope of the grain. A piece of lumber whose grain runs parallel to the long axis of the member will have maximum strength for that species. As the slope of the grain with respect to the axis increases, the strength of the member decreases, Figure 13.30.

KNOTS

A knot occurs where a branch emerges from the tree trunk, Figure 13.31(a). The growth rings in the trunk of a tree are interlaced with the growth rings of its branches. Within the trunk, the growth rings of a branch form a cone whose end points toward the center of the trunk and whose diameter gradually increases toward the bark. Hence, the grain of wood in the vicinity of a branch is not straight, but highly disturbed from straightness (yielding cross-graining), Figure 13.31(b). Consequently, the presence of a knot in a member reduces its strength. The more numerous the knots in a member, the lower its strength.

The adverse effect of a knot on the member's strength is more pronounced if the knot is a *loose knot*. A loose knot results when the branch dies during the tree's growth and the successive growth rings of the trunk encircle this dead branch. The death of the branch may be

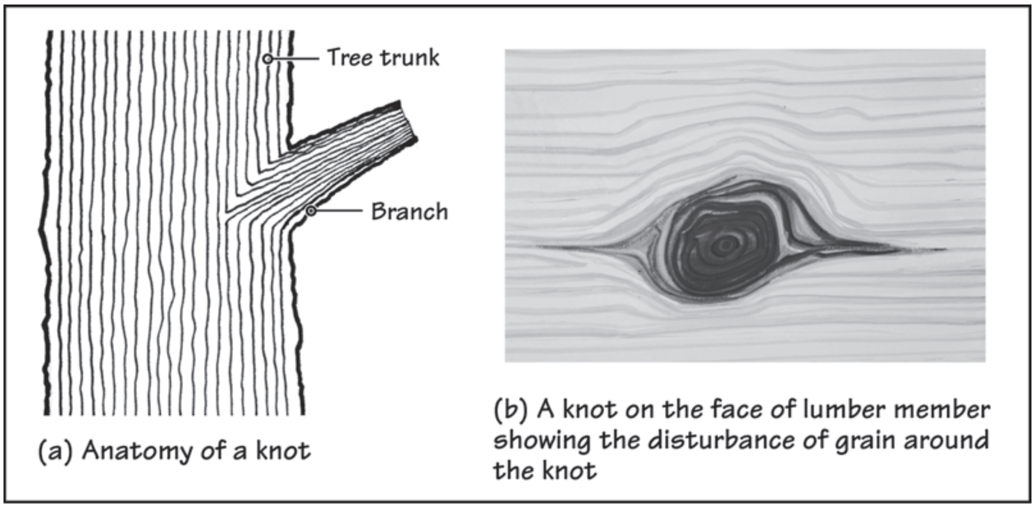

Tree trunk
Branch
(a) Anatomy of a knot
(b) A knot on the face of lumber member showing the disturbance of grain around the knot

FIGURE 13.31 **(a)** Anatomy of a knot. **(b)** Grain orientation in the vicinity of a knot.

biologically caused—for example, by the overshadowing of the branch by the upper parts of the tree—or mechanically caused—such as by the effect of strong wind or a hail storm.

A loose knot reduces the strength of wood substantially, and if rotting occurs in the knot, a *knot hole* results. A knot that is not loose, but is tightly intergrown with the adjoining tissue, is referred to as an *encased knot*.

Apart from the number, size, and type of knots (encased or loose), the location of the knot within the member also affects its strength. A knot located on or near the longitudinal axis of the member does not affect the strength as adversely as a knot located near the edges of the member, Figure 13.32. Remember that in a member subjected to bending (such as a beam, floor joist, rafter, and so on), the bending stresses are maximum at the extreme edges of the member and zero at the center (neutral axis).

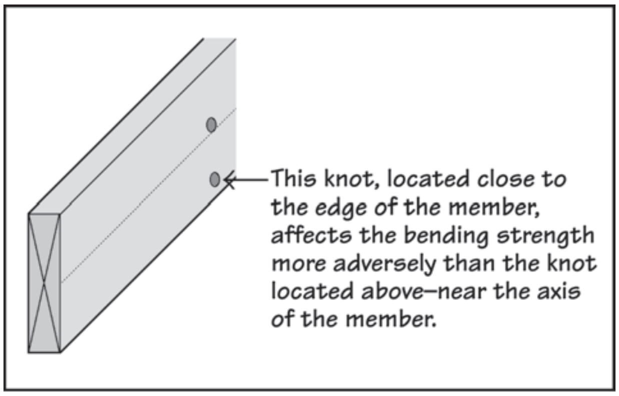

This knot, located close to the edge of the member, affects the bending strength more adversely than the knot located above—near the axis of the member.

FIGURE 13.32 Effect of the location of a knot on the bending strength of a member.

CHECKS, SHAKES, AND SPLITS

Checks, shakes, and splits are separations of wood fibers. A *check* is separation of wood fibers along the rays (perpendicular to growth rings). It is caused by the drying of wood and occurs at the ends of the member and also on its faces, Figure 13.33(a). It results from the fact that the surfaces of wood dry faster than its interior.

A *shake* is separation of wood fibers along the growth rings, Figure 13.33(b). It occurs during the growth of the tree and is not due to drying. A *split* occurs at the ends of a member and is a complete separation of wood fibers through the entire end, Figure 13.33(c). It is believed to be caused by a weakness that occurred during the growth of the tree and was aggravated during drying.

WANE

A *wane* is the absence of wood or the presence of bark at the corner or the edge of a piece that results from the sawing process, Figure 13.34. Like knots, checks, splits, and shakes, wanes also reduce the strength of the member. Therefore, their sizes and numbers are taken into account in the grading of lumber.

13.11 LUMBER GRADING

In North America, each piece of lumber used for structural framing is graded and so stamped, as shown in Figure 13.35. The grading is done by an independent inspection agency, which employs trained inspectors. Each piece is visually examined on all of its four surfaces for growth characteristics, such as the slope of grain, knots, checks, and shakes. An inspector's trained eyes can determine the grade of a piece of lumber within a few seconds. Such a grading method is referred to as *visual grading*, as opposed to *machine grading*, described later.

In visual grading, the inspection agency grades lumber according to the grading rules prescribed by a grading rules–writing agency. In North America, there are seven *grading rules–writing agencies* (six in the United States and one in Canada), which also function as inspection agencies (see Table 13.4).

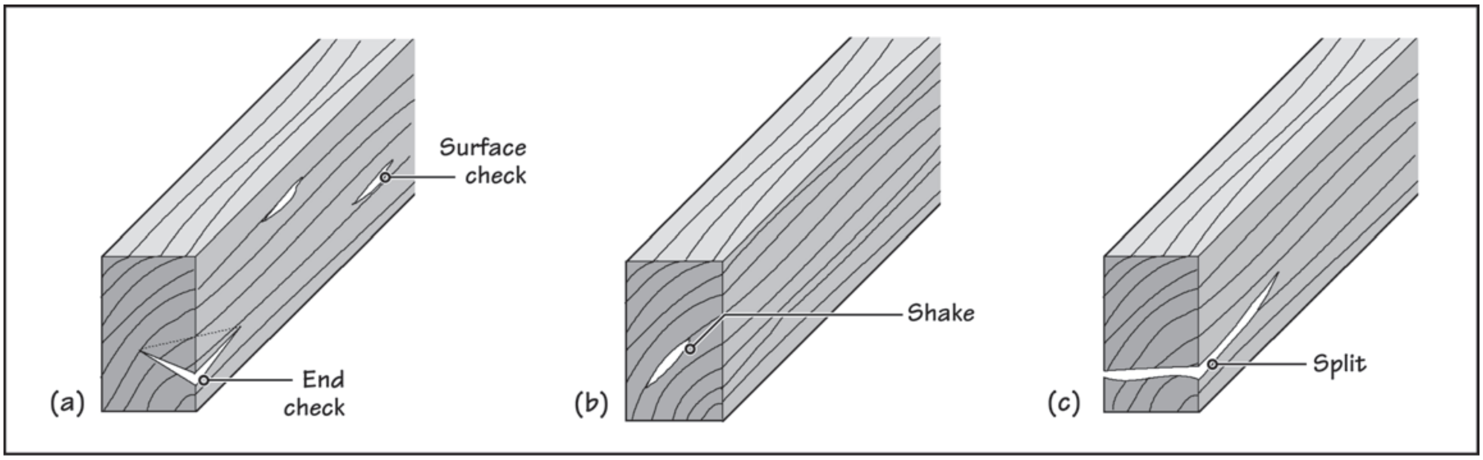


FIGURE 13.33 Check, shake, and split in lumber.

COMPUTERIZED VISUAL GRADING

While grading of lumber through the eyes of trained inspectors has been the historical norm, most lumber mills are now replacing it with computerized visual grading. The rationale is that what human eyes can observe and analyze a lumber member (straightness of grain, size, quality, and location of knots, splits, and other defects), it can be accomplished more reliably by digital cameras using three-dimensional imaging of the member, known as *computer-based vision technology*.

Therefore, the modern visual grading of lumber, while retaining all the essential features of the earlier human grading, is now done through digital imaging. The printing of grade stamps on members is also automated using digital printers which are integrated with manufacturing operations, Figure 13.36. In the earlier system, the grade stamp was pressed on the member using a rubber stamp.

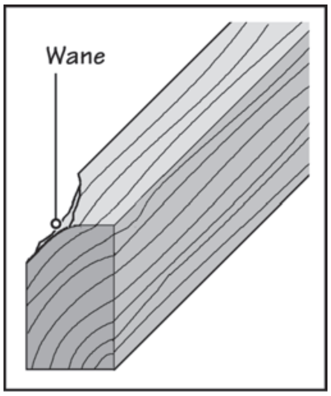


FIGURE 13.34 A wane on a piece of lumber.

VISUAL GRADING—DIMENSION LUMBER GRADES AND GRADE STAMPS

Although the seven rules-writing agencies have different grading rules for boards and timbers, their grading rules for dimension lumber are identical and are referred to as the *National Grading Rules* (*NGR*) *for Dimension Lumber*. According to these rules, dimension lumber can carry any one of the several grades shown in Figure 13.37.

Two typical grade stamps for dimension lumber are shown in Figure 13.38. Note that a grade stamp identifies the following items:

- Species of lumber
- Moisture content at the time of surfacing
- The mill that produced the piece
- The inspection (grading) agency
- The structural grade

Examples of grade stamps of various agencies for dimension lumber available in North America are given in the Principles in Practice section at the end of this chapter.

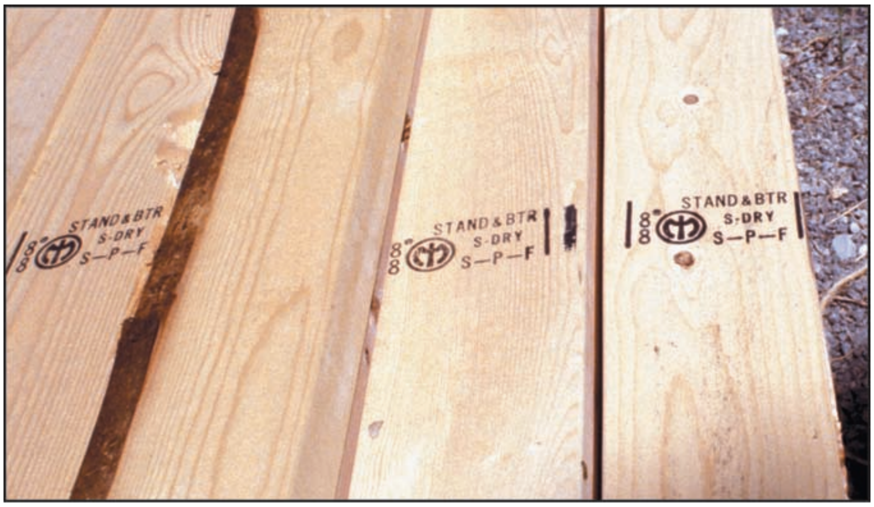


FIGURE 13.35 Grade stamps on lumber members.

TABLE 13.4 GRADING RULES–WRITING AGENCIES

U.S. Agencies
Northeastern Lumber Manufacturers Association, Inc. (NELMA)
Northern Softwood Lumber Bureau (NSLB)
Redwood Inspection Service (RIS)
Southern Pine Inspection Bureau (SPIB)
West Coast Lumber Inspection Bureau (WCLIB)
Western Wood Products Association (WWPA)
Canadian Agency
National Lumber Grades Authority (NLGA)

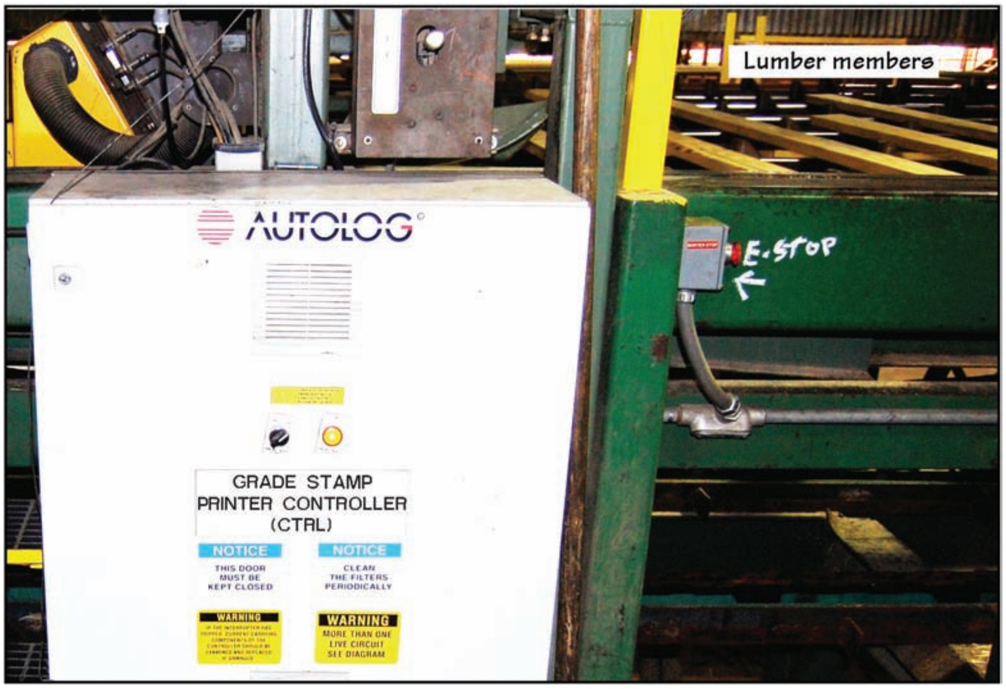
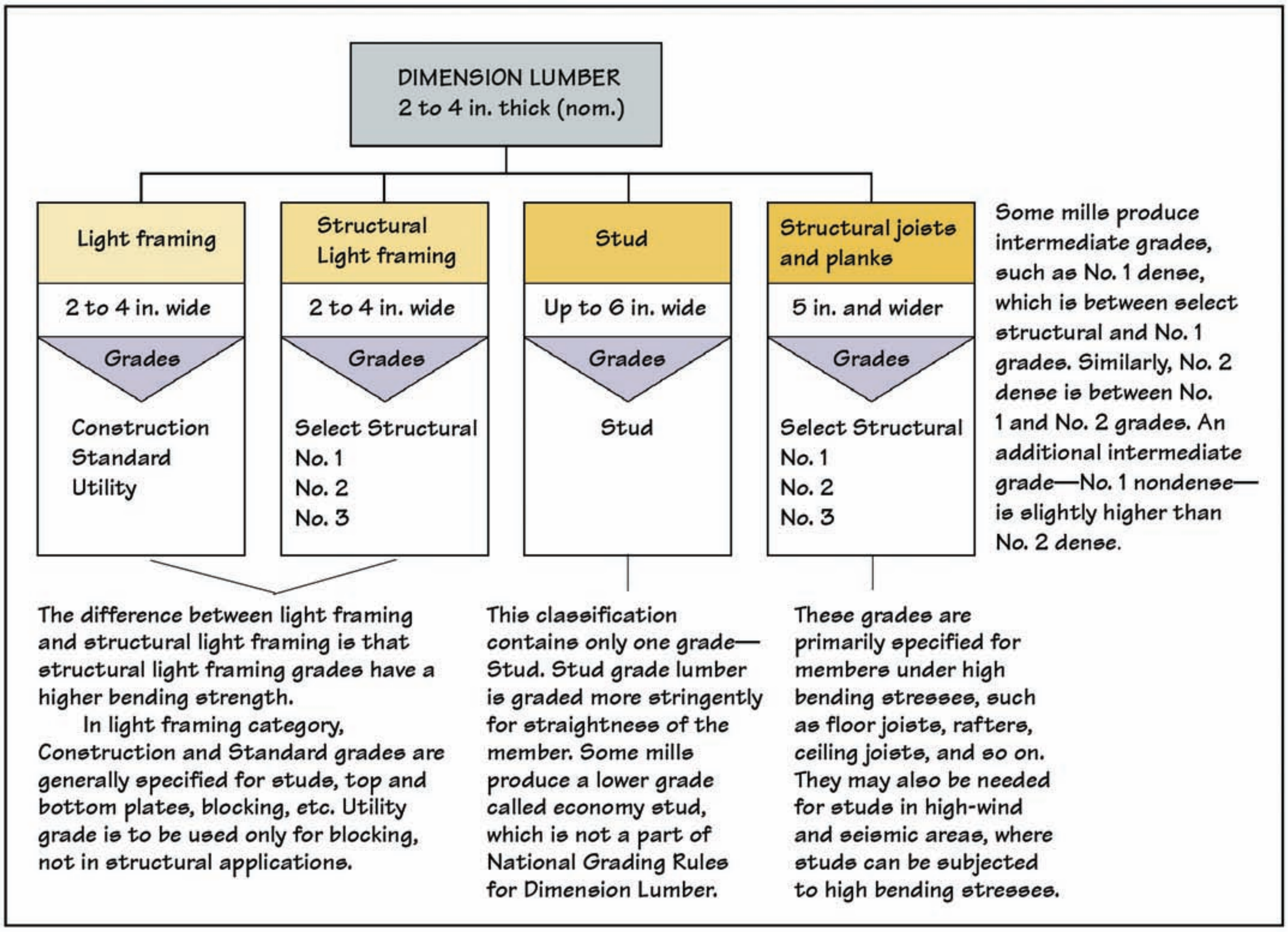

Lumber members
AUTOLOG
E-STOP
GRADE STAMP
PRINTER CONTROLLER
(CTRL)
NOTICE
THIS DOOR MUST BE KEPT CLOSED
NOTICE
CLEAN THE FILTERS PERIODICALLY
WARNING
WARNING
MORE THAN ONE LIVE CIRCUIT SEE DIAGRAM

FIGURE 13.36 In computerized visual grading, the grade stamps are printed on lumber members using digital printing technology, replacing the earlier system that used grading crew to rubber stamp lumber members.


DIMENSION LUMBER
2 to 4 in. thick (nom.)
Light framing
2 to 4 in. wide
Grades
Construction
Standard
Utility
Structural Light framing
2 to 4 in. wide
Grades
Select Structural
No. 1
No. 2
No. 3
Stud
Up to 6 in. wide
Grades
Stud
Structural joists and planks
5 in. and wider
Grades
Select Structural
No. 1
No. 2
No. 3

Some mills produce intermediate grades, such as No. 1 dense, which is between select structural and No. 1 grades. Similarly, No. 2 dense is between No. 1 and No. 2 grades. An additional intermediate grade—No. 1 nondense—is slightly higher than No. 2 dense.

The difference between light framing and structural light framing is that structural light framing grades have a higher bending strength.

In light framing category, Construction and Standard grades are generally specified for studs, top and bottom plates, blocking, etc. Utility grade is to be used only for blocking, not in structural applications.

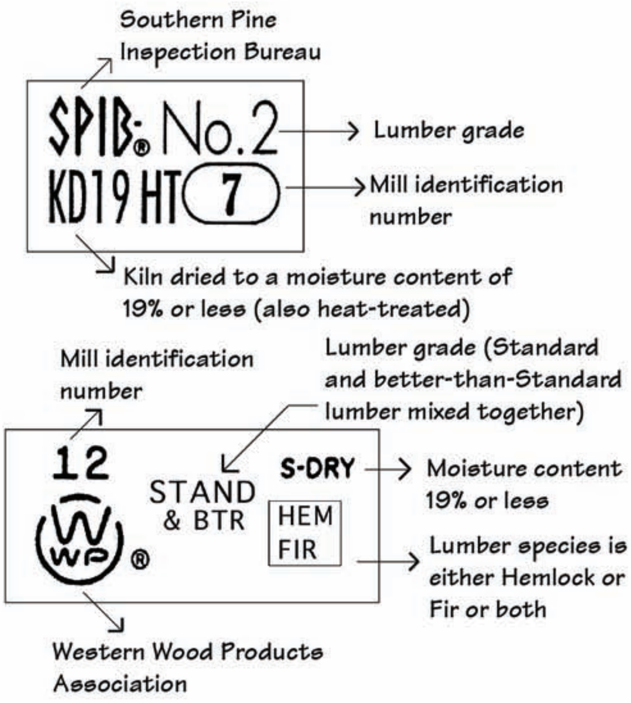
This classification contains only one grade—Stud. Stud grade lumber is graded more stringently for straightness of the member. Some mills produce a lower grade called economy stud, which is not a part of National Grading Rules for Dimension Lumber.

These grades are primarily specified for members under high bending stresses, such as floor joists, rafters, ceiling joists, and so on. They may also be needed for studs in high-wind and seismic areas, where studs can be subjected to high bending stresses.

FIGURE 13.37 Various grades for dimension lumber.

VISUAL GRADING—ALLOWABLE STRESSES FROM THE GRADE STAMP

Through extensive structural testing of solid lumber members, the allowable stress values and the modulus of elasticity of lumber of various species and grades have been compiled by the wood industry. Figure 13.39 shows these values for one species group—southern pine lumber. Its purpose is simply to illustrate the nature of the data available for the design of wood frame buildings.


Southern Pine Inspection Bureau
SPIB® No.2
KD19 HT 7
Lumber grade
Mill identification number
Kiln dried to a moisture content of 19% or less (also heat-treated)
Mill identification number
Lumber grade (Standard and better-than-Standard lumber mixed together)
12
STAND & BTR
S-DRY
HEM FIR
WWP®
Moisture content 19% or less
Lumber species is either Hemlock or Fir or both
Western Wood Products Association

Southern pine grade stamp does not specify lumber species because Southern pine is a mixture of four species: Longleaf pine, Shortleaf pine, Slash pine, and Loblolly pine. These species are mixed together because they are almost equivalent in appearance and performance.

Grade stamps of other agencies include species information. However, two or more species may be grouped together. For example, the WWPA grade stamp given below shows that two species—Hemlock and Fir—have been combined together. Similarly, a species designation "S-P-F" means that Spruce, Pine, and Fir have been grouped together.

To distinguish Canadian S-P-F designation from the United States designation, S-P-F from the United States is called S-P-F (south) or S-P-F^s. Similarly, D-Fir (North) indicates that it is Canadian Douglas Fir.

Heat Treatment (HT) of Lumber is intended to eliminate pests and to make it suitable for packaging industry, which utilizes a great deal of dimension lumber. Heat treatment is not required for lumber used in construction. Heat treatment standards require that lumber be subjected to a kiln temperature of 133°F (56°C) for a minimum of 30 min. Kiln drying of lumber for construction purposes is generally more stringent.

FIGURE 13.38 Typical grade stamps. A comprehensive grade stamp list of North American lumber is given at the end of this chapter.

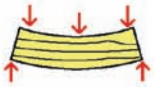
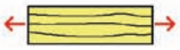
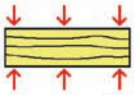
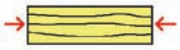
Lumber cross section	Structural property	Lumber grade						
		Select structural	No. 1	No. 2	No. 3 & Stud	Construction	Standard	Utility
Thickness 2 in. to 4 in. (nominal) Width 2 in. to 4 in. (nominal)	Allowable bending stress, F_b (psi) 	2,350	1,500	1,100	650	875	475	225
	 Allowable tensile stress parallel to grain, F_t (psi)	1,650	1,000	675	400	500	275	125
	Allowable shear stress, F_v (psi)	175	175	175	175	175	175	175
	 Allowable compressive stress perpendicular to grain, $F_{c\perp}$ (psi)	565	565	565	565	565	565	565
	 Allowable compressive stress parallel to grain, $F_{c//}$ (psi)	1,900	1,650	1,450	850	1,600	1,300	850
	Modulus of elasticity, E (10^3 psi)	1,800	1,600	1,400	1,300	1,400	1,200	1,200

FIGURE 13.39 Allowable stresses and modulus of elasticity of visually graded southern pine lumber of selected cross-sectional sizes and lumber grades (based on normal loads and moisture content ≤19%). Adapted from "New Design Values for Southern Pine Lumber" June 1, 2013, Southern Forest Products Association (SFPA). For a comprehensive listing of allowable stresses for all lumber species, grades, and cross-sectional dimensions, refer to National Design Specifications for Wood Construction (2015) published by the American Wood Council (AWC).

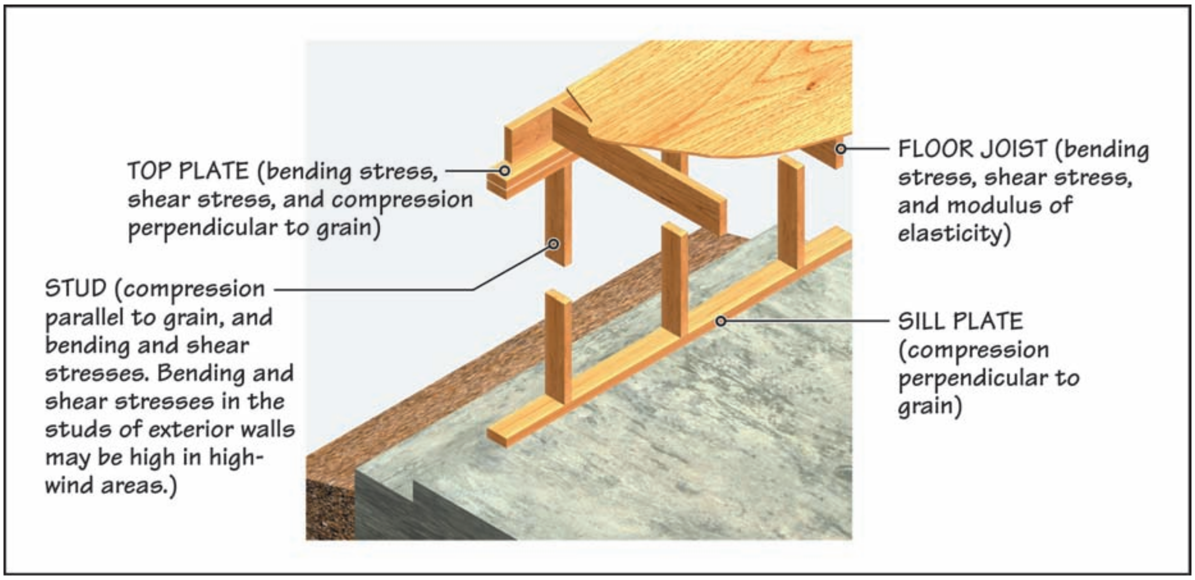

TOP PLATE (bending stress, shear stress, and compression perpendicular to grain)
STUD (compression parallel to grain, and bending and shear stresses. Bending and shear stresses in the studs of exterior walls may be high in high-wind areas.)
FLOOR JOIST (bending stress, shear stress, and modulus of elasticity)
SILL PLATE (compression perpendicular to grain)

FIGURE 13.40 Structural properties that are critical for the design of various members of a wood frame building.

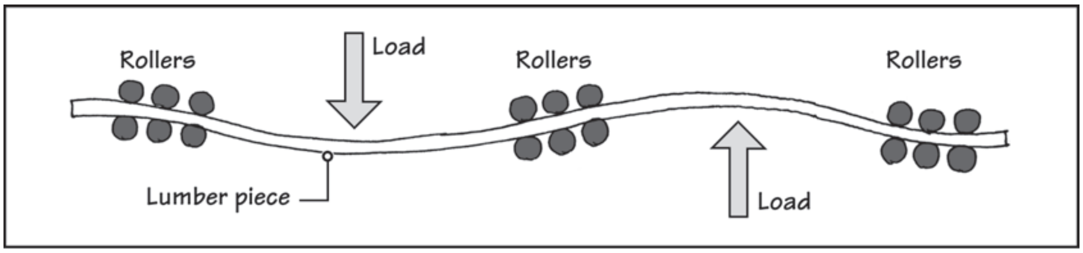

Rollers
Load
Rollers
Rollers
Lumber piece
Load

FIGURE 13.41 Outline of the equipment used for machine stress-rated lumber. Load-deflection information is fed into a computer, which automatically determines the values of the modulus of elasticity and allowable bending strength of the lumber.

Figure 13.40 shows the types of stresses that are critical for the structural design of various members of a conventional wood frame building.

MACHINE STRESS-RATED LUMBER

Lumber grading discussed previously is called visual grading because it is done either by trained inspectors or by computer-based vision technology. Whereas the lumber used in the structural frame of a typical wood building is visually graded, the lumber used in more demanding structural applications, such as wood trusses, is machine graded. Machine-graded lumber is referred to as *machine stress-rated (MSR) lumber*, or simply *machine-rated lumber*.

In MSR lumber, the stiffness (modulus of elasticity) of a piece of lumber is determined by a nondestructive testing procedure in which the piece is subjected to a given load and its deflection is noted, Figure 13.41. Because various strength properties of lumber are directly related to its modulus of elasticity (E), they can be derived from the already established statistical relationships between E and the lumber's strength properties.

Although a certain amount of visual inspection of lumber is necessary even in MSR lumber, machine grading is heavily automated, using high-speed equipment to obtain stiffness and other properties, including the affixing of the grade stamp.

An MSR grade stamp is similar to the grade stamp of visually graded lumber, except that in place of the grade mark in visually graded lumber, the MSR stamp gives E and F_b values. Thus, in the grade stamp of Figure 13.42, the lumber has the following properties: allowable bending stress (F_b) = 2,400 psi and modulus of elasticity (E) = 2.0×10^6 psi. Other structural properties of this piece, such as the allowable compressive stress, shear stress, and so on, are obtained from the tables prepared by the lumber industry.

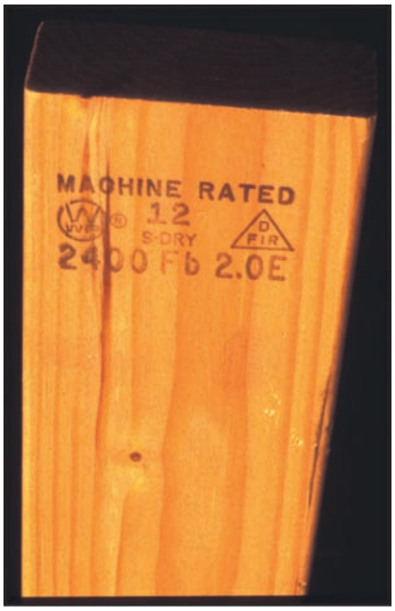

MACHINE RATED
12
S-DRY
D FIR
2400 Fb 2.0E

FIGURE 13.42 A typical grade stamp on a machine stress-rated (MSR) lumber.

13.12 DURABILITY OF WOOD

Like any other material, wood is subject to deterioration. Mechanical and chemical deterioration are the two most common ways in which a building material deteriorates. Mechanical deterioration of wood is due to physical wear, such as the abrasion caused by foot traffic or wheeling equipment on a floor. Other causes of mechanical wear, which occur primarily in wood exposed to the exterior climate, are (a) erosion of the material by wind and water,* (b) material fatigue caused by its repeated expansion and contraction, and (c) deterioration caused by freeze-thaw cycles.

Chemical deterioration is due to the effect of chemicals (acids and alkalies) in the environment and the chemical breakdown of wood's constituents by the ultraviolet rays of the sun. Generally, mechanical and chemical deterioration of wood is of little importance, because the major cause of wood's deterioration is biological, referred to as *biodeterioration*.

BIODETERIORATION

Biodeterioration is caused by living organisms that use wood as food. Two such groups of organisms consume wood:

- Fungi
- Insects

Deterioration of wood caused by fungi is called *fungal decay* or simply the *decay of wood* (also called *rotting*). Land-based insects that consume wood are *termites*, and water-based wood-eating insects are called *marine borers*. In addition to termites and marine borers, there are carpenter ants, which, though not using wood as food, can nest inside it, thereby weakening the wood to some degree.

13.13 FUNGAL DECAY

Unlike other plants, fungi cannot manufacture their own food but live off the food produced by other plants. Because wood is mainly cellulose and lignin, it is an excellent source of food for these parasites.

Not all forms of fungi invade the cell structure of wood. Those that do are the ones that cause structural damage to wood (decay). As the decay-causing fungus consumes this food, the strength of wood decreases, which is usually accompanied by a change in the external appearance of wood.

For instance, a type of fungus that consumes cellulose (white in color) makes wood turn more brown, and the fungus that consumes lignin (brown in color) makes wood turn whiter. *Brown rot* and *white rot* are the terms used for the two forms of decay.

Because fungus is a plant life, four factors are necessary for its survival and growth:

- Oxygen
- Mild temperature
- Water
- Food

When any one of these four elements is removed, fungal decay cannot take place. Thus, wood completely immersed in water at all times does not decay due to the absence of oxygen. Similarly, fungal decay does not generally occur in extremely cold climates. The most favorable temperature range for fungal growth and survival is 70°F to 85°F (20 to 30°C), as it is with most other plants. Thus, in a seasoning kiln, where high-temperature air is used to dry the wood, most types of fungi perish.

PREVENTING FUNGAL DECAY

Because it is not possible to control temperature and the supply of oxygen in building assemblies, the only methods available to prevent fungal decay are: (a) to control the supply of water in wood and (b) to make wood toxic to fungi.

It has been found that if the moisture content in wood is less than 20%, fungal decay does not occur. That is why 19% moisture content has been fixed as the dividing line between dry and green lumber. Specifying dry lumber and keeping it dry (below 19% moisture content) is the best insurance against decay. This fact highlights the importance of ventilating attics and crawl spaces in wood structures, because excessive moisture buildup in confined spaces can raise the moisture content of wood above 20%.

Although the lumber that is not exposed to rain or groundwater may be kept dry, this is not true with the lumber exposed to a water source. Therefore, exterior lumber, lumber buried in the ground, or lumber close to or in contact with the ground will decay. Two options are available to prevent the decay of exposed lumber:

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*The erosion due to wind is caused by dust and grit in the air. Thus, in terms of the weatherability of materials, wind behaves as a low-intensity sand blasting and rain serves as water blasting.

- Use of naturally decay-resistant species.
- Use of preservative-treated lumber.

Whereas the heartwood of a tree is generally more decay resistant than its sapwood, the heartwood of a few species, such as cedar, redwood, cypress, and black locust, have a high degree of decay resistance. These species may be used in decay-prone situations. Preservative-treated lumber is treated with chemicals that are toxic to fungi and insects.

13.14 TERMITE CONTROL

Most termite damage in buildings is caused by subterranean termites. Subterranean termites live in underground colonies. Due to their distaste for light, they normally cannot reach above-ground wood. However, they can build tubular mud tunnels over foundation walls and piers to reach the above-ground wood.

Because they can obtain water from the ground, termites do not have to depend on the water in the wood. Thus, although wood with a moisture content of less than 20% is not subject to fungal decay, it is vulnerable to termites if the termites can reach the wood.

Subterranean termites are more commonly found in warm climates; the termite hazard is usually higher in warm, damp climates than in warm, dry climates. The hazard is relatively low in colder regions. Figure 13.43 shows the termite-infestation probability map of the United States.

NOTE

Termites and Building Materials

Cellulose-based materials are food for termites, but termites also attack plastics. They are known to chew through cable shields, plastic laminates, and plastic foam insulation. The use of below-ground plastic foam insulation is, therefore, not recommended in termite-infested regions.

REDUCING (OR PREVENTING) TERMITE DAMAGE

A multipart strategy is required to reduce or prevent termite damage in wood buildings. For wood members not buried in the ground, all or a combination of the following strategies are generally recommended:

- Maintain distance between wood and ground.
- Provide a soil barrier, that is, a chemical soil treatment.
- Use naturally decay-resistant or preservative-treated wood.
- Use a termite shield.
- Inspection and remediation.

The best line of defense against termites is to provide sufficient distance between the ground and the wood member, supplemented by frequent inspection to ensure that no mud tunnels exist. Figure 13.44 shows some of the commonly recommended construction details for preventing termite attack.

In most wood frame buildings, preservative-treated lumber is specified only for the sill plate when it is anchored to the concrete or masonry foundation. All other framing lumber

NOTE

Importance of a Termite Barrier

Experts estimate that termites can go through a space as small as $\frac{1}{24}$ in. Therefore, a concrete slab-on-grade should be without visible cracks. Hollow concrete masonry foundations must be fully grouted, and the termite shield must be carefully soldered at all joints.

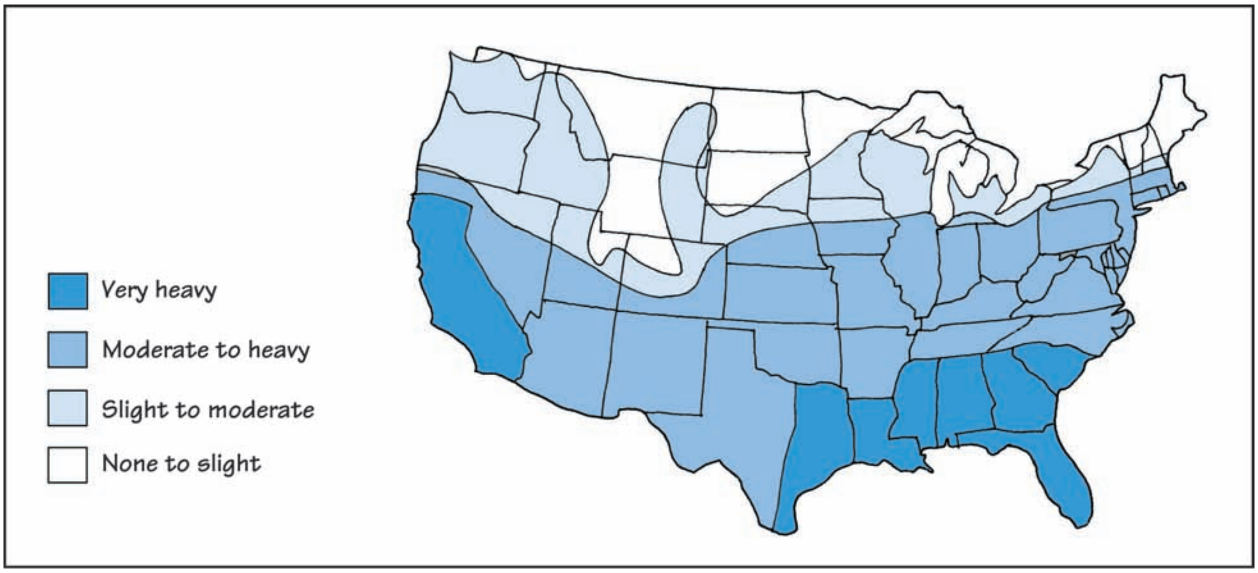


FIGURE 13.43 Termite infestation probability map of the United States. This map should be regarded only as approximate and must be verified with its original source and the information obtained from the building code of the jurisdiction.
Source: United States Department of Agriculture Economic Research Service.

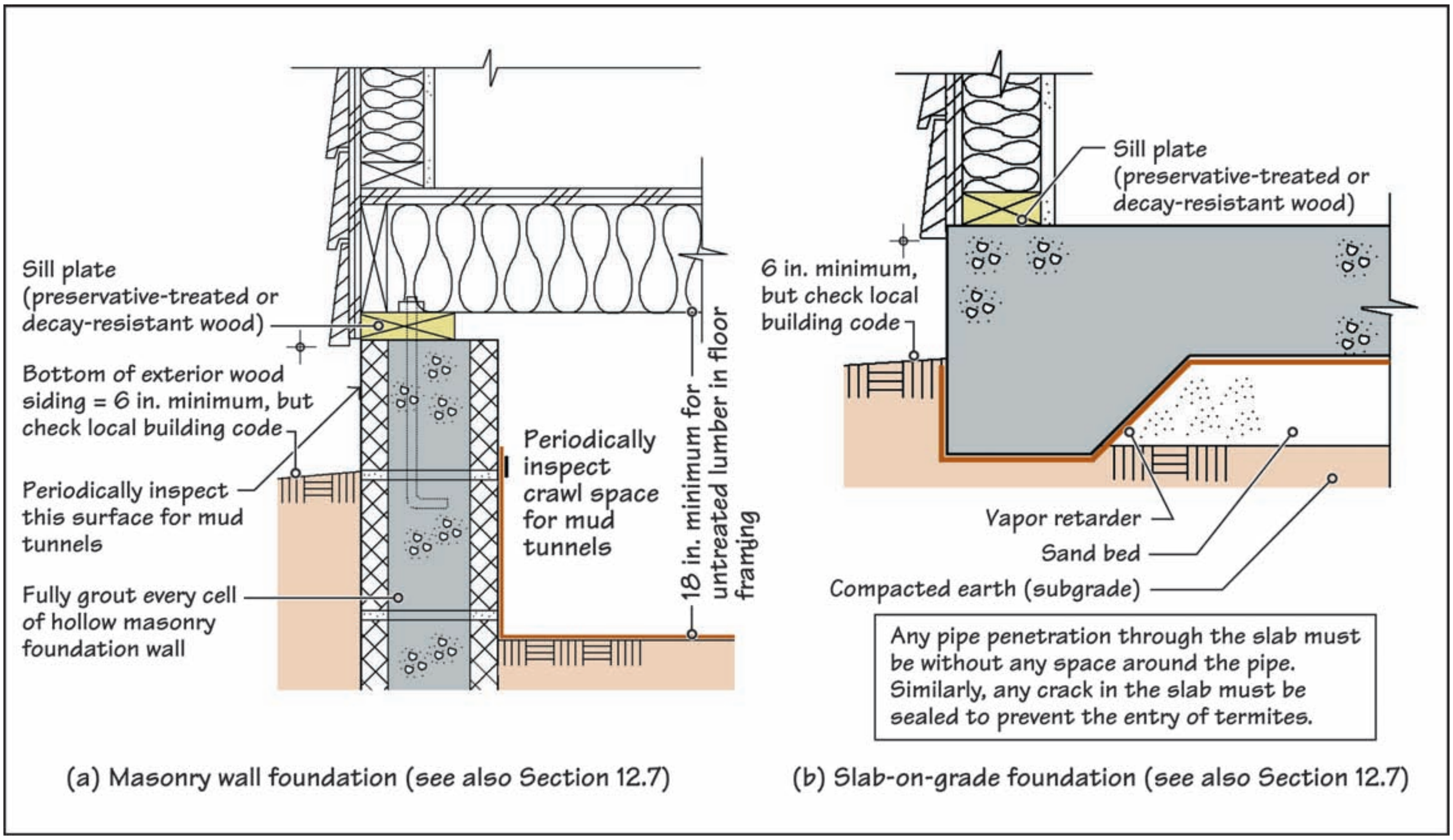

Sill plate
(preservative-treated or
decay-resistant wood)
Bottom of exterior wood
siding = 6 in. minimum, but
check local building code
Periodically inspect
this surface for mud
tunnels
Fully grout every cell
of hollow masonry
foundation wall
Periodically
inspect
crawl space
for mud
tunnels
18 in. minimum for
untreated lumber in floor
framing
Sill plate
(preservative-treated or
decay-resistant wood)
6 in. minimum,
but check local
building code
Vapor retarder
Sand bed
Compacted earth (subgrade)
Any pipe penetration through the slab must
be without any space around the pipe.
Similarly, any crack in the slab must be
sealed to prevent the entry of termites.
(a) Masonry wall foundation (see also Section 12.7)
(b) Slab-on-grade foundation (see also Section 12.7)

FIGURE 13.44 The use of preservative-treated or decay-resistant lumber in a conventional wood frame building.

is usually untreated lumber. Wood floor joists over a crawl space are required to be of preservative-treated or decay-resistant species only if the distance between the bottom of the joists and the ground is less than 18 in. Wood beams less than 12 in. above the ground must satisfy the same criterion.

Treating the soil around foundation walls and the soil below concrete slabs-on-grade or basement slabs provides additional protection against termites. Although the method of application of the chemicals (e.g., aldrin or dieldrin—0.5% in water emulsion) is fairly simple, it is recommended that the application be done by a specialist agency. Booster applications may be needed in some locations every few years.

In locations subjected to heavy or very heavy termite hazard (based on local experience), the use of a termite shield is recommended. A termite shield is generally made of galvanized sheet steel profiled with a drip-edge-type bend. Termites are unable to maneuver around this bend in building mud tunnels. All wood must be placed above termite shields, Figure 13.45.

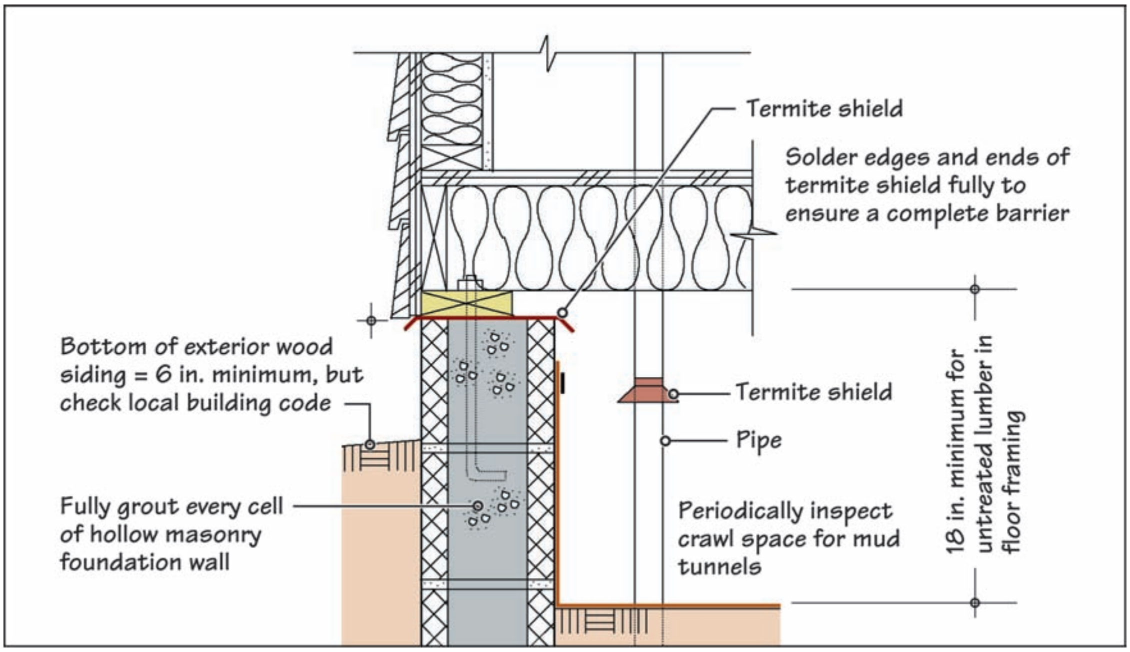

Termite shield
Solder edges and ends of
termite shield fully to
ensure a complete barrier
Bottom of exterior wood
siding = 6 in. minimum, but
check local building code
Termite shield
Pipe
Fully grout every cell
of hollow masonry
foundation wall
Periodically inspect
crawl space for mud
tunnels
18 in. minimum for
untreated lumber in
floor framing

FIGURE 13.45 The use of a termite shield is recommended as an additional protection in regions with heavy infestation of termites.

13.15 PRESERVATIVE-TREATED WOOD

The use of naturally decay-resistant species gives limited protection against termites. Additionally, their supply is small and decreasing. Therefore, the use of decay-resistant species is infrequent.

The most effective and the most commonly used method of achieving termite protection is through the use of preservative-treated lumber. Therefore, preservative-treated lumber is commonly specified for outdoor decks, fences, verandahs, porches, and lumber buried in the ground (fence poles, wood retaining walls, wood foundations, etc.). Because the preservative is pressure injected into lumber, preservative-treated lumber is also referred to as *pressure-treated lumber*.

The preservatives used in pressure-treated lumber enable it to resist insect and fungal attack. To be effective, they must be toxic to these organisms, nondamaging to wood, and relatively safe to humans. Three types of preservatives are commonly used for the purpose:

- Creosote
- Oil-borne preservatives
- Waterborne preservatives

Creosote is the oldest and the most effective preservative against all forms of wood-eating insects, including marine borers. A distillate of coal tar, creosote is black to deep brown in color and is relatively insoluble in water. It is commonly used in railroad ties, utility poles, highway guardrail posts, marine bulkheads, and piles. Because frequent human contact with creosote is not recommended, creosote-treated lumber is not used in structural framing, decks, patios, benches, and so on. Creosote-treated lumber cannot be painted.

Pentachlorophenol (or simply penta) is the most commonly used oil-borne preservative. It is effective against fungi and land-based insects but not against marine borers. It is commonly used for bridge timbers and utility poles.

WATERBORNE PRESERVATIVES

Wood treated with waterborne preservatives has several applications. Common applications of waterborne preservative–treated wood are on outdoor decks, fences, gazebos, playground equipment, structural framing, and highway noise barriers. Commonly used preservatives are:

- Chromated copper arsenate (CCA)
- Alkaline copper quat (ACQ)
- Copper azole (CA)
- Sodium borates (SBX)

CCA is a waterborne mixture of the compounds of copper, chromium, and arsenic, giving the name *chromated copper arsenate*. Copper is toxic to fungi, and arsenic is an insecticide. Chromium is added to lock the preservative into wood.

CCA was the most widely used waterborne preservative until 2003. However, due to environmental concerns, it is no longer allowed for use in residential building components such as outdoor decks, landscape timbers, fencing, and playground structures. CCA is also not allowed in plywood, glulaminated lumber, and laminated veneer lumber. It will continue to be used in noise barriers, vehicular bridges, and some industrial structures.

ACQ and CA are replacing CCA for residential uses. Most wood preservers provide warranties of performance similar to those formerly provided for CCA. Both ACQ and CA have high retentivity in wood, and their leaching from wood is minimal. SBX-treated lumber is limited to indoor applications such as sill plates and interior framing lumber because of its solubility in water.

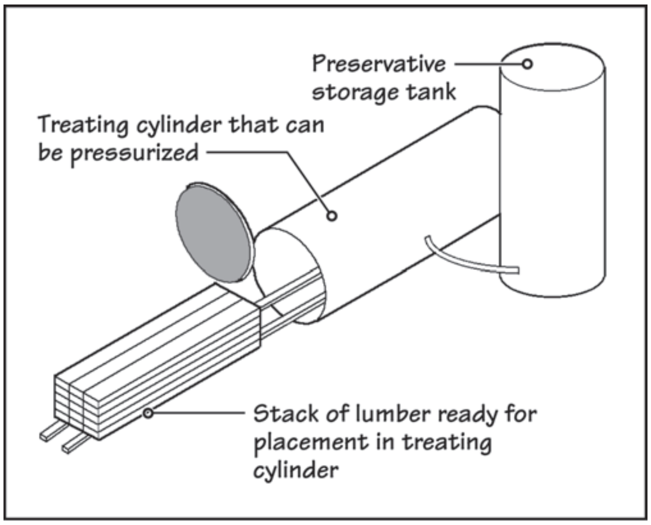

Preservative storage tank
Treating cylinder that can be pressurized
Stack of lumber ready for placement in treating cylinder

FIGURE 13.46 Outline of the equipment used for pressure treating lumber with a preservative.

PRESSURE TREATMENT WITH WATERBORNE PRESERVATIVES

Pressure treatment is done by placing lumber members in a cylinder, filling the cylinder with waterborne preservatives in liquid form, and applying the correct amount of pressure, Figure 13.46. The pressure helps to inject the preservative into cell cavities. The treated lumber is subsequently taken out of the cylinder and dried.

A piece of lumber kiln dried (to less than or equal to 19% moisture content) after treatment carries the stamp KDAT, meaning *kiln dried after treatment*. The amount of preservative injected into wood is a function of the hazard to which it would be subjected, as shown in Table 13.5.

Not all wood species can be effectively pressure treated; more permeable ones are better for treatment. Some of the commonly treated species are shown in Table 13.6. Of these, some species need incisions (slits along the grain of wood) prior to treatment to help push the preservative into the required depth of the member.

Because of the presence of copper in CCA, ACQ, and CA, pressure-treated lumber is generally greenish in color. However, a coloring agent can be added to the preservative to change the color of treated lumber to one that approaches the color of untreated lumber. Treated lumber may be stained, painted, or sealed.

Treated lumber carries a treater's stamp. It is either an imprint (ink stamp) on the lumber or, more commonly, a plastic tag stapled to an end of the member, referred to as an *end tag* in the industry, Figure 13.47. Note that treated lumber carries two stamps: One stamp refers to the mill that originally produced that member and its grade, and the other stamp is the treater's stamp (or end tag). Figure 13.48 shows the information that is provided on treated lumber's end tag or stamp.

In addition to special handling precautions, treated wood has special disposal restrictions. For instance, treated wood must not be burned in stoves or fireplaces because of the toxic chemicals that it releases. The fasteners (nails and screws) and other steel components (joist hangers, etc.) used with treated wood must be of galvanized steel or stainless steel because of the corrosive effect of the preservative.

TABLE 13.5 RETENTION OF WATERBORNE -PRESERVATIVES AND LOCATION OF TREATED LUMBER OR PLYWOOD IN A BUILDING

Location of lumber or plywood	Retention (lb/ft^3)
Aboveground	0.25
Ground contact	0.40
Permanent wood foundation	0.60
Structural poles	0.60
Fresh water immersion	0.60
Salt water immersion[a]	2.50

[a] Marine borers are usually found in salt water or brackish water.

TABLE 13.6 MAJOR PRESSURE-TREATABLE SOFTWOOD SPECIES

Southern pine	Douglas fir
Ponderosa pine	Hem-fir
Red pine	Western larch
Jack pine	Redwood
Sugar pine	
White pine	

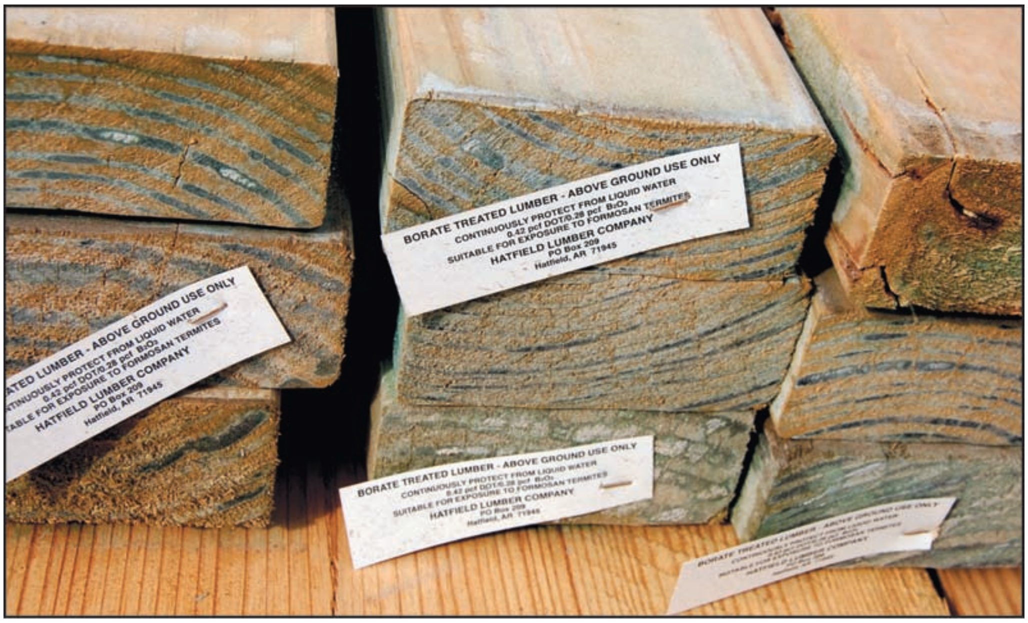

BORATE TREATED LUMBER - ABOVE GROUND USE ONLY
CONTINUOUSLY PROTECT FROM LIQUID WATER
0.42 pcf DOT/0.28 pcf B₂O₃
SUITABLE FOR EXPOSURE TO FORMOSAN TERMITES
HATFIELD LUMBER COMPANY
PO Box 209
Hatfield, AR 71945

FIGURE 13.47 A pressure-treated lumber pile with end tags.

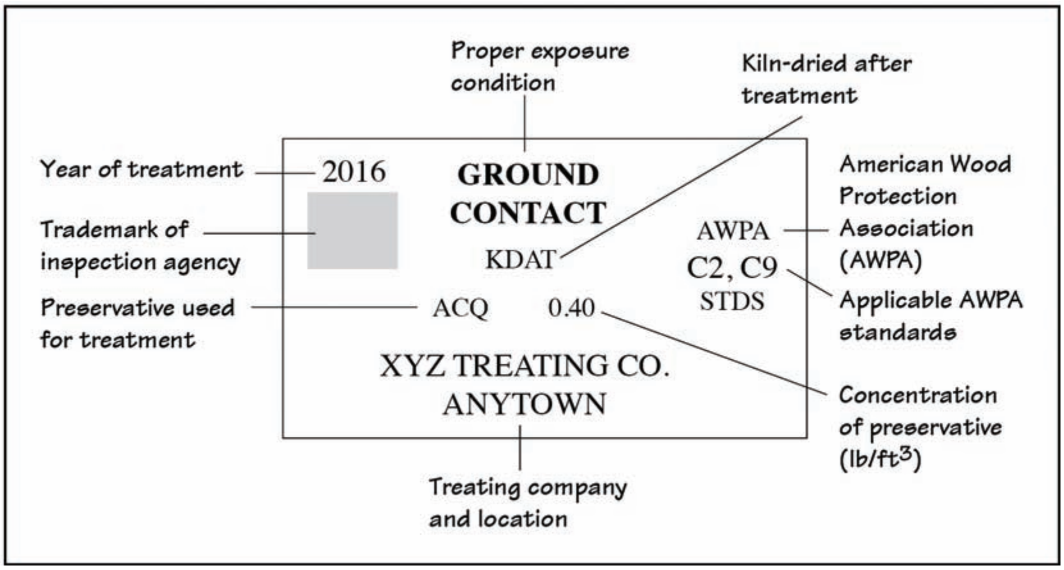

Proper exposure condition
Kiln-dried after treatment
Year of treatment
2016
GROUND CONTACT
Trademark of inspection agency
KDAT
AWPA
American Wood Protection Association (AWPA)
C2, C9
STDS
Applicable AWPA standards
Preservative used for treatment
ACQ
0.40
XYZ TREATING CO.
ANYTOWN
Concentration of preservative (lb/ft3)
Treating company and location

FIGURE 13.48 Information provided on an ink stamp or an end tag on pressure-treated lumber.

13.16 FIRE-RETARDANT-TREATED WOOD

Fire-retardant-treated wood (FRTW) is lumber or plywood that has been pressure treated with chemicals that retard the development of fire. Although not recognized as a noncombustible material (such as steel, concrete, or masonry), FRTW is permitted by building codes in non-load-bearing situations, where only noncombustible materials are allowed. FRTW is required to have a flame spread rating of 25 or less (see Chapter 7 for the definition of flame spread rating). Other uses of fire-retardant treatment are in wood roofing shingles and shakes. Each FRTW piece must carry the Underwriters Laboratory identification.

FOCUS ON SUSTAINABILITY

Sustainability Features of Lumber

Wood is biodegradable and the most rapidly renewable building material. It is the only material that is theoretically inexhaustible and uses the most renewable form of energy for its production—solar energy. The only nonrenewable energy used in wood's production is in sawing, planing, and dressing of wood to its finished form. Additionally, although the production of other materials creates environmental pollution from gaseous and liquid emissions, the production of wood (the growth of trees) produces oxygen that purifies the environment. The use of wood as a building material is, therefore, a sustainable practice.

However, because forests are essential for the survival of life on earth, excessive and uncontrolled harvesting of trees to obtain wood is damaging to the environment. The wood industry has, therefore, introduced third-party certification of lumber and engineered wood products. The certification of wood is a means of ensuring that the forests are managed for sustainability through:

Maintenance of biodiversity of plant and animal species in forests.
Conservation of soil and water quality in forests.
Controlled harvesting of trees for socioeconomic benefits.
Sustained improvement in forest management practices.

Certification of wood is voluntary, and a number of agencies conduct wood certification under the rules established by the Forest Stewardship Council (FSC). Certified wood is more expensive. However, it is expected that with increasing use of certified wood, a greater number of commercial forests will participate in the certification of their products, bridging the cost gap between certified and uncertified wood.

FSC is a global umbrella organization with a small permanent secretariat in Oaxaca, Mexico, that accredits wood-certifying agencies in various countries. Wood certified by an FSC-accredited certifier (e.g., the SmartWood and Scientific Certification systems) carries the FSC logo.

The FSC stamp is an index of sustainable forest-management practices. It does not include other issues of sustainability, such as embodied energy and emissions of volatile organic compounds from engineered wood products.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

33. Which of the following lumber cross sections is that of a dimension lumber?
- **a.** 4 × 8
- **b.** 6 × 8
- **c.** 1 × 8
- **d.** 1 × 12
- **e.** 6 × 12

34. Which of the following is not a lumber grade?
- **a.** No. 1
- **b.** No. 2
- **c.** No. 3
- **d.** No. 4
- **e.** Construction

35. The basis for distinguishing lumber as *board*, *dimension lumber*, and *timber* is the
- **a.** species of lumber.
- **b.** strength of lumber.
- **c.** cross-sectional dimensions of lumber.
- **d.** length of lumber.
- **e.** durability of lumber.

36. A lumber grade stamp must include information on the cross-sectional dimensions of lumber.
- **a.** True
- **b.** False

37. A lumber grade stamp must include the mill identification number.
- **a.** True
- **b.** False

38. Which of the following grades will not apply to a 2 × 8 lumber?
- **a.** No. 1
- **b.** No. 2
- **c.** No. 3
- **d.** Construction

39. Which of the following grades can only be used as blocking?
- **a.** No. 1
- **b.** No. 2
- **c.** Construction
- **d.** Utility
- **e.** Standard

40. Lumber used for structural framing members, such as studs, floor joists, and rafters, is graded using
- **a.** only visual inspection.
- **b.** only machine grading.
- **c.** both visual and machine grading must be used to arrive at lumber's grade.

41. Preservative-treated lumber is effective
- **a.** only against termite attack.
- **b.** only against fungal attack.
- **c.** against both fungi and termites.

42. A termite shield is generally made of
- **a.** asphalt-treated felt.
- **b.** galvanized sheet steel.
- **c.** lead sheet.
- **d.** kraft paper.

43. Wood certified by the Forest Stewardship Council (FSC) is available
- **a.** only in the United States.
- **b.** in the United States and Canada.
- **c.** in the United States, Canada, and Mexico.
- **d.** in (c) and several other countries.

REVIEW QUESTIONS

1. Describe the essential differences between softwood and hardwood trees. Give at least three commonly used species of each.
2. What is the difference between heartwood and sapwood? Explain.
3. What does the term *SPF* mean? What is the difference between SPF^{s} and SPF? Explain.
4. Using sketches and notes, explain why wood is stronger along the grain than across the grain.
5. Using sketches and notes, explain how to distinguish graphically between framing lumber and finished lumber in cross-sectional drawings.
6. In visually grading of lumber, what do graders typically look for in the piece of lumber? Explain.
7. What information is typically provided on the grade stamp of visually graded lumber? Explain with the help of an example of a typical grade stamp.
8. With the help of a sketch, explain how machine-rated lumber is graded. What information does the grade of machine-rated lumber provide?
9. Explain how fungal decay of lumber can be prevented.
10. With the help of a sketch, explain what a termite shield is and where in a building it is typically provided.

CHAPTER 14

Materials for Wood Construction–II (Engineered Wood Products, Fasteners, and Connectors)

CHAPTER OUTLINE

14.1 GLULAM MEMBERS

14.2 STRUCTURAL COMPOSITE LUMBER—LVL AND PSL

14.3 WOOD I-JOISTS

14.4 WOOD TRUSSES

14.5 WOOD PANELS

14.6 PLYWOOD PANELS

14.7 OSB PANELS

14.8 SPECIFYING WOOD PANELS—PANEL RATINGS

14.9 FASTENERS FOR CONNECTING WOOD MEMBERS

14.10 SHEET METAL CONNECTORS

There is a growing number of wood products that are produced using techniques that extend beyond sawing and planing. One of the earliest examples—plywood—originated from a laminating process that can be traced back to ancient Egypt and China. However, it was not until the invention of waterproof adhesives in the 1930s that plywood became the first commercially produced *manufactured wood product*.

Manufactured wood products are made by bonding together lumber members, wood veneers, wood strands, wood particles, and other forms of wood fibers to produce a composite material. Their manufacturing process eliminates defects and weak points in wood (or spreads them over the product), giving a stiffer, stronger, and more homogeneous material than lumber. The process also utilizes wood materials that would have otherwise become a waste.

Two types of manufactured wood products are used in construction:

- Engineered wood products
- Industrial wood products

Engineered wood products are those that are engineered for structural applications. They include glue-laminated wood, structural composite lumber, wood I-joists, plywood, oriented strandboard, and wood trusses.

Industrial wood products include particle board, medium-density fiberboard (MDF), and high-density fiberboard (HDF), also called *hardboard.* Particle board is commonly used for cabinet work, furniture, heavy-duty shipping containers, and so on. MDF is used as a replacement for solid lumber. It has a smooth surface that allows precise machining to form complex and intricate moldings. Hardboard is commonly used as floor underlayment (Section 14.8).

This chapter begins with a discussion of various engineered wood products. It then deals with fasteners and connectors used in wood frame construction.

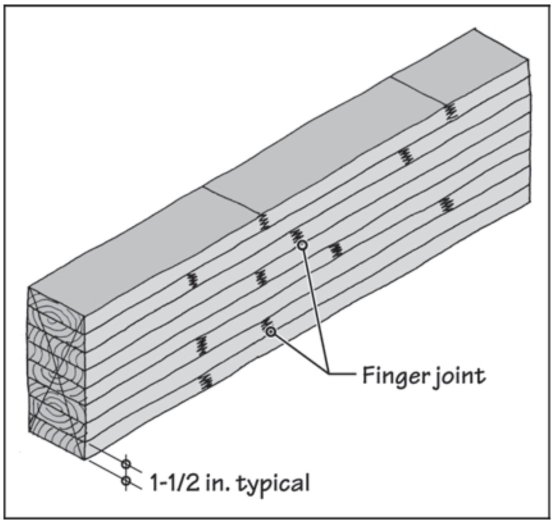


FIGURE 14.1 Anatomy of a glulam beam. A glulam beam is typically made by gluing together $1\frac{1}{2}$-in.-thick laminations of solid sawn lumber.

14.1 GLULAM MEMBERS

Sawn lumber has several limitations where large cross-sectional wood members are required to span long distances between structural supports. Some of these limitations are as follows:

- Large sawn lumber cross sections can be obtained only from trees with large girths. Such trees are generally protected from harvesting. Additionally, trees with excessively long life spans make lumber farming uneconomical.
- Large sawn lumber cross sections cannot be dried to an acceptable moisture content.
- Because sawn lumber is naturally grown, there is little control over its structural properties.

Glue-laminated wood (referred to as *glulam*) is the response to these limitations. It is made from individual lengths of dimension lumber that are glued together to form large cross sections. The individual lengths are joined horizontally (face laminated) as well as vertically (end jointed), Figure 14.1. The ends are either finger-joined or butt-jointed.

Laminating is an effective way of using short lengths of high-grade sawn lumber obtained by eliminating pieces that are of low grade due to knots, shakes, and splits. Because glulam is generally made from dimension lumber, it uses lumber that has been dried to a fairly low moisture content, generally less than 15%. Additionally, laminating allows the use of smaller trees harvested from younger forests.

The adhesive used between laminations is of high strength and is fully water resistant. Consequently, a glulam member is stronger and stiffer than a sawn lumber of the same dimensions. The use of water-resistant adhesive means that a glulam member can be used in externally exposed conditions without delaminating along adhesive lines.

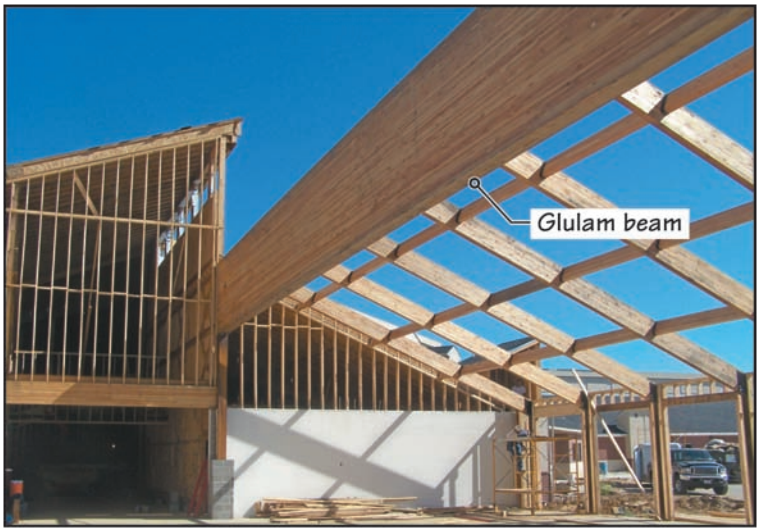


FIGURE 14.2 A 12-in.-wide, 7-ft-deep glulam beam over a long span (82 ft) in Gunter Primary School, Gunter, Texas. Architect: SAI Architects, Keller, Texas. (Photo courtesy of APA—The Engineered Wood Association)

USES AND SIZES OF GLULAM MEMBERS

The most common use of glulam members is for long-span beams, Figure 14.2. Other uses are for heavy columns, Figure 14.3, and heavy trusses, Figure 14.4. In some situations, glulam members are specified because their large cross sections provide greater fire resistance. A fire resistance rating of up to 1 h is obtainable with unprotected glulam members.

Glulam manufacturers produce beams of standard cross sections that are cut to the required lengths. Because 2-by (i.e., $1\frac{1}{2}$-in.-thick) lumber is used in producing glulam beams, its depth is generally in multiples of $1\frac{1}{2}$ in., such as $7\frac{1}{2}$ in., 9 in., or $10\frac{1}{2}$ in.

The width of glulam beams varies depending on the width of the dimension lumber used. Standard beam widths vary from nearly 3 in. to nearly 14 in. Wider beams can be custom produced. Theoretically, a glulam member can be made to any cross-sectional size and length by gluing pieces of dimension lumber side-by-side and face-to-face, Figure 14.5. However, limitations of transportation to the construction site and installation of the member must be considered in choosing a large glulam member.

Because glulam is made from small wood sections under controlled conditions, it can also be curved along its length. Thus, arches and other contours can be easily obtained in glulam, Figure 14.6. In curved glulam members, laminations are generally $\frac{3}{4}$ in. thick instead of the standard thickness of $1\frac{1}{2}$ in.

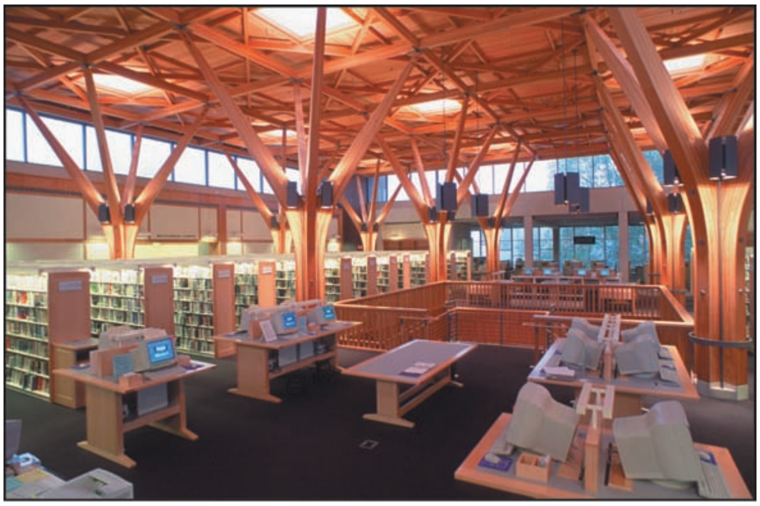


FIGURE 14.3 Glulam columns used in Beaverton Public Library, Beaverton, Oregon. Architect: Thomas Hacker and Associates, Portland, Oregon. (Photo courtesy of APA—The Engineered Wood Association)

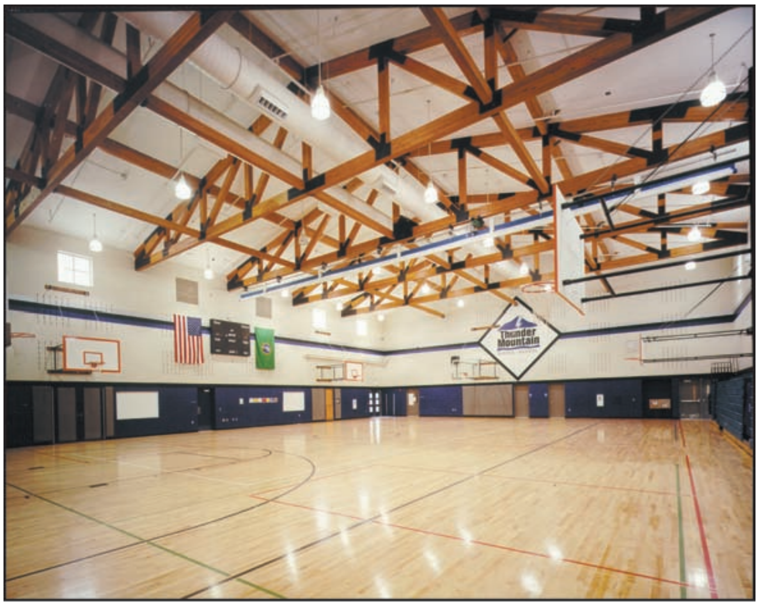


FIGURE 14.4 Glulam trusses used in the gymnasium of Thunder Mountain Middle School, Enumclaw, Washington. Architect: BLRB Architects, Tacoma, Washington. (Photo courtesy of APA—The Engineered Wood Association)

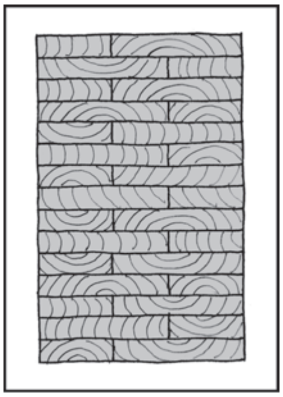


FIGURE 14.5 Large cross sections of glulam members are made by gluing laminations side-by-side and face-to-face.

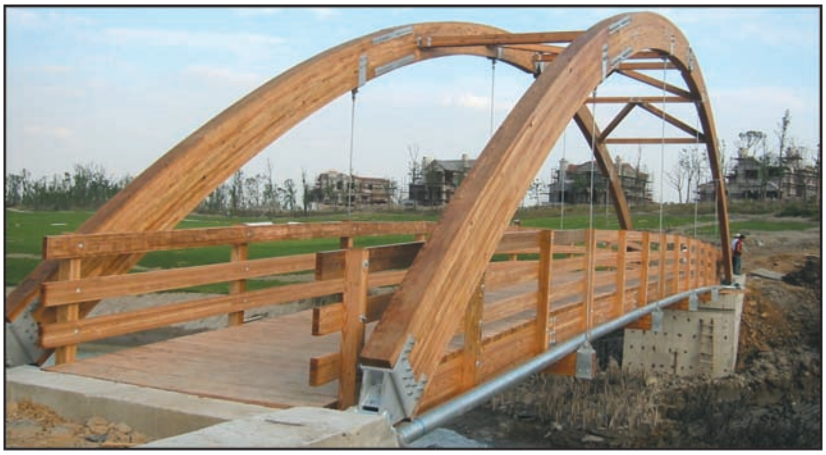


FIGURE 14.6 Sheshan Golf Course bridge near Shanghai, China. (Photo courtesy of APA—The Engineered Wood Association)

BALANCED AND UNBALANCED GLULAM BEAMS

Balanced glulam beams are symmetrical in lumber quality above and below the beam's mid-depth. In an unbalanced beam, the quality of the lumber used in upper laminations is different from that of the lumber used in lower laminations to account for the fact that the lower half of the beam will be in tension and the upper half of the beam will be in compression. Unbalanced beams are, therefore, stamped with *TOP* to ensure their correct placement, Figure 14.7. They can be used only as single-span beams, Figure 14.8.

Balanced glulam beams are more versatile because they can be used for any span condition. However, they are generally used where the beams are continuous over two or more supports, because a continuous beam is subjected to tension and compression on both faces of the beam at different locations. Similarly, a beam with an overhang (cantilever) will also require the use of a balanced glulam beam.

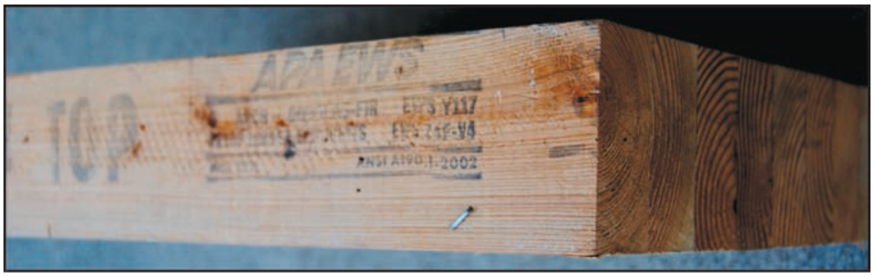


FIGURE 14.7 An unbalanced glulam beam showing the beam's top face.

NOTE

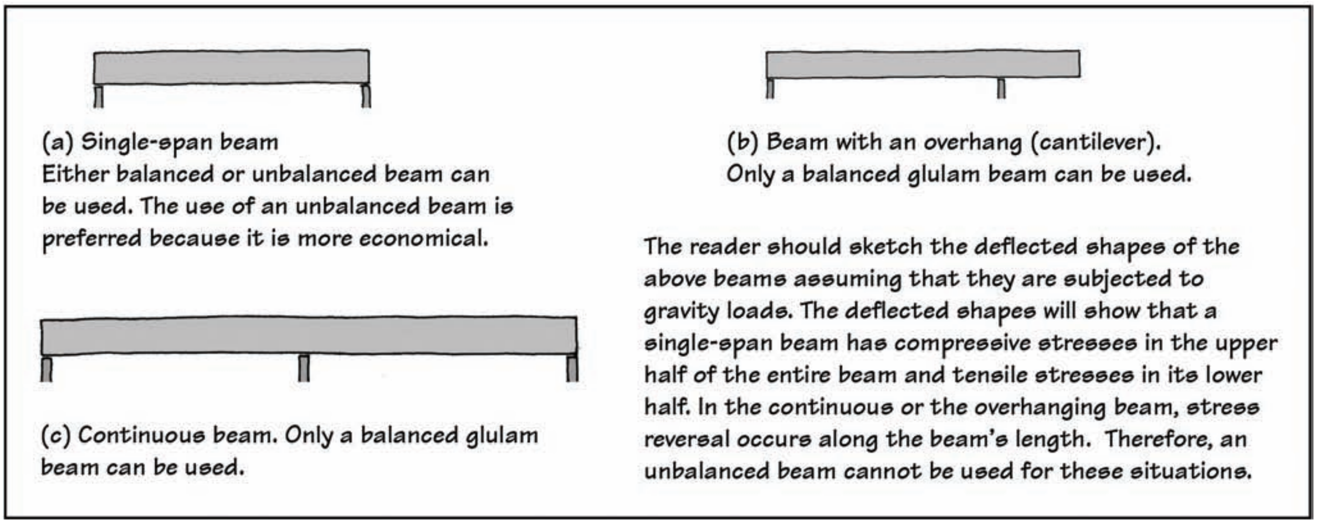
APA, PFS, and TECO

Three U.S. organizations provide third-party certification and quality control of glulam and other engineered wood (EW) products: APA—The Engineered Wood Association, PFS Corporation, and TECO Corporation.

APA originated as the certifier of plywood products. At that time, APA was the acronym for *American Plywood Association*. With the introduction of other engineered wood products, it has changed its name to "APA—The Engineered Wood Association" to better describe its new role.

PFS and TECO are sister organizations. TECO deals with the quality certification of wood panels—plywood and oriented strandboard—and PFS deals with the other engineered wood products.

Of these three organizations, APA has by far the largest market share at the present time.


(a) Single-span beam
Either balanced or unbalanced beam can be used. The use of an unbalanced beam is preferred because it is more economical.

(b) Beam with an overhang (cantilever).
Only a balanced glulam beam can be used.

The reader should sketch the deflected shapes of the above beams assuming that they are subjected to gravity loads. The deflected shapes will show that a single-span beam has compressive stresses in the upper half of the entire beam and tensile stresses in its lower half. In the continuous or the overhanging beam, stress reversal occurs along the beam's length. Therefore, an unbalanced beam cannot be used for these situations.

(c) Continuous beam. Only a balanced glulam beam can be used.

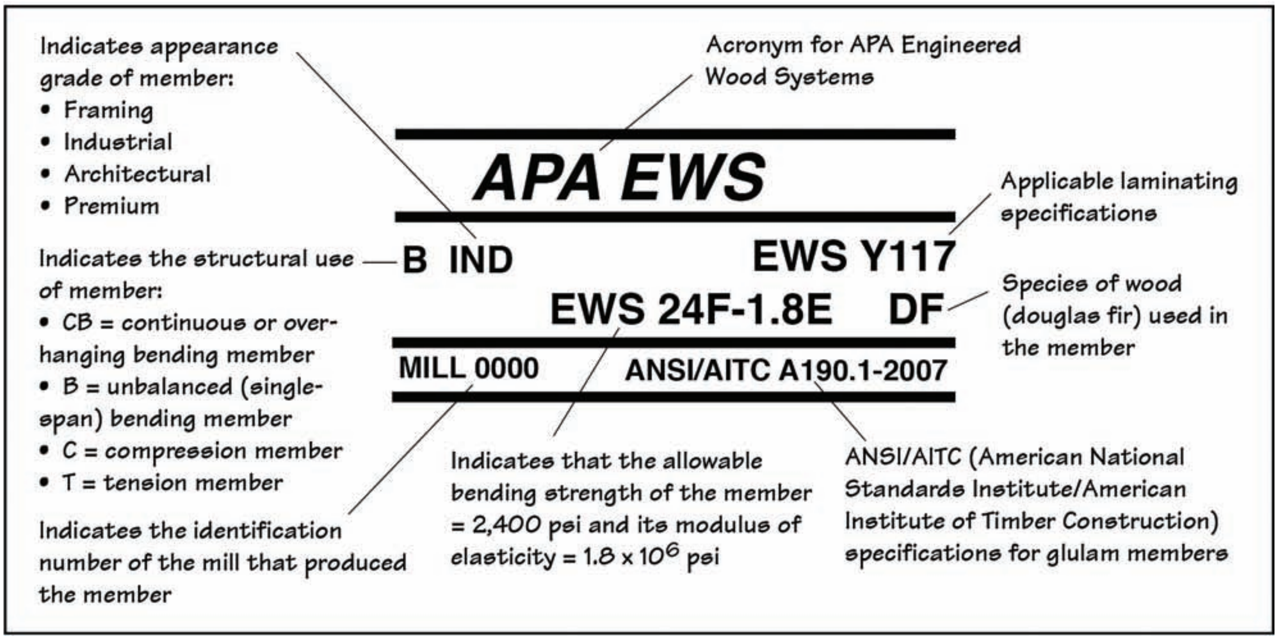
FIGURE 14.8 The use of balanced and unbalanced glulam beams in a single-span beam, an overhanging beam, and a continuous beam.

SPECIFYING GLULAM MEMBERS—GLULAM MEMBER GRADES

Most glulam producers in the United States conform to the quality certification mechanism developed by APA—The Engineered Wood Association, which requires each glulam member to be grade stamped. Among other information, the grade stamp on a glulam member provides the structural properties of the beam and its appearance. The appearance of a glulam member is classified into one of the following four grades:

- *Framing Appearance Grade*—the lowest appearance grade in which the glue smears and squeeze-out, knots, and splits are acceptable. Framing grade glulam members should not be exposed to view.
- *Industrial Appearance Grade*—commonly specified in situations where the appearance of the member is relatively unimportant, such as in a warehouse, or if the member is to be covered with a finish material. Some manufacturers make industrial grade glulam beams called *headers*. These are beams whose thickness is consistent with the commonly used widths of wood frame walls. Thus, glulam headers are made to widths of $3\frac{1}{2}$ in., $5\frac{1}{2}$ in., and $7\frac{1}{4}$ in. The $3\frac{1}{2}$-in.-thick header can be used over an opening in a wood frame wall with 2 × 4 studs. A $5\frac{1}{2}$-in.-thick header is used in a wall with 2 × 6 studs.
- *Architectural Appearance Grade*—an appearance grade that is intermediate between those of industrial and premium grades.
- *Premium Appearance Grade*—a grade commonly specified where the appearance of the beam is important.

A typical APA grade stamp on a glulam member is shown in Figure 14.9.



Indicates appearance grade of member:
- Framing
- Industrial
- Architectural
- Premium

Acronym for APA Engineered Wood Systems

Applicable laminating specifications

Indicates the structural use of member:
- CB = continuous or overhanging bending member
- B = unbalanced (single-span) bending member
- C = compression member
- T = tension member

Species of wood (douglas fir) used in the member

Indicates the identification number of the mill that produced the member

Indicates that the allowable bending strength of the member = 2,400 psi and its modulus of elasticity = 1.8×10^6 psi

ANSI/AITC (American National Standards Institute/American Institute of Timber Construction) specifications for glulam members

FIGURE 14.9 A typical grade stamp on a glulam member.

14.2 STRUCTURAL COMPOSITE LUMBER—LVL AND PSL

Laminated veneer lumber (LVL) is produced by gluing together dried wood veneers that are approximately $\frac{1}{8}$ in. thick. The wood grain in all veneers runs in the same direction, unlike the grain in plywood, where the veneers are cross-grained between laminations (see Section 14.5). Thus, like sawn lumber, LVL is stronger along the grain and weaker across the grain.

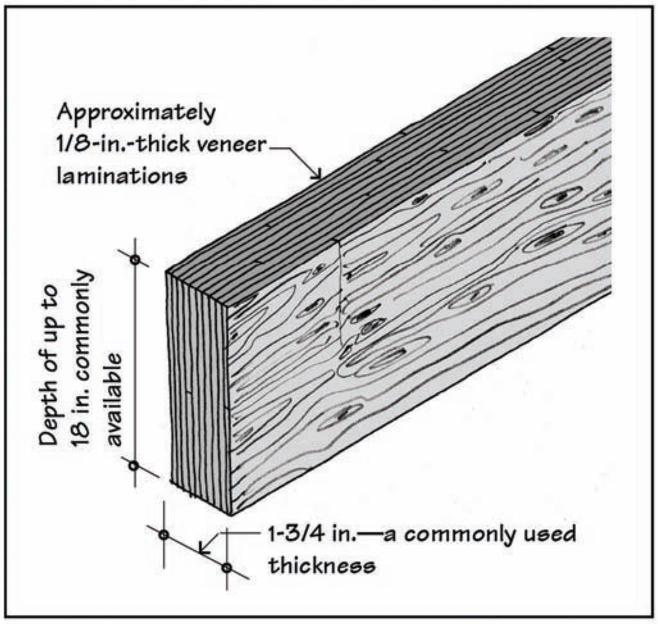


FIGURE 14.10 A typical LVL member.

LVL is generally used as floor joists and rafters. Therefore, it is usually made to a finished thickness of $1\frac{3}{4}$ in. and to depths of up to 18 in., Figure 14.10. The thickness of $1\frac{3}{4}$ in. (compared to $1\frac{1}{2}$ in. for sawn lumber) provides a greater fastening surface for floor or roof sheathing. Other thicknesses, such as $3\frac{1}{2}$ in. and $5\frac{1}{4}$ in., are also available. The $3\frac{1}{2}$-in.-thick LVL members are generally used as headers in 2 × 4 wood stud walls. If $3\frac{1}{2}$-in.-thick LVL is not available, two $1\frac{3}{4}$-in.-thick LVL members can be nailed together to make a $3\frac{1}{2}$-in.-thick member.

Because LVL is made from veneers that are dried to a moisture content of approximately 12% (the equilibrium moisture content in a typical building interior), it is less likely to warp or split compared to sawn lumber. Because the defects in veneers are cut away, LVL is stronger than sawn lumber of the same dimensions. Like glulam, LVL allows the use of smaller trees.

LVL members are produced by gluing veneers to form large billets, approximately 2 ft × 4 ft in cross section and nearly 80 ft long. These billets are then sawn to yield the desired (smaller) LVL members.

PARALLEL STRAND LUMBER

A variation of LVL is called *parallel strand lumber* (PSL). PSL is made by gluing together narrow strands of veneer in place of wide veneers. The strands are made by chopping the veneers into strips about $\frac{1}{2}$ in. wide and 8 ft long. Like LVL, PSL is first made into large billets, which are then sawn to the required dimensions. Both LVL and PSL are proprietary to each manufacturer. Manufacturers provide structural data and other recommendations that must be adhered to in the use of LVL and PSL members. LVL and PSL together are referred to as *structural composite lumber* (SCL).

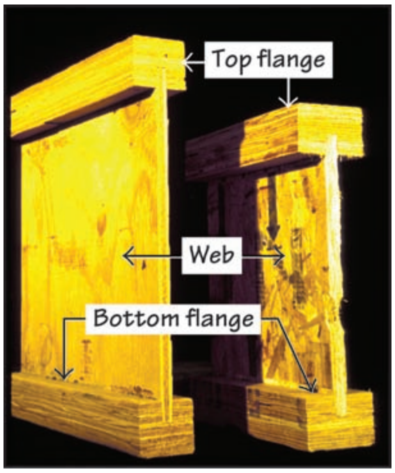
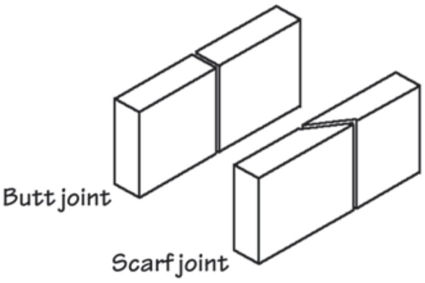


FIGURE 14.11 Typical wood I-joists.



14.3 WOOD I-JOISTS

Wood I-joists (so named because of their I-shaped cross section) are made by gluing wood flanges to a wood web, Figure 14.11. The flanges are made of either sawn lumber or LVL. LVL has gained greater acceptance because I-joist flanges must be jointless, which is more easily done with LVL members because they are available in much longer lengths than sawn lumber.

The web in a wood I-joist is either of plywood or oriented-strandboard (OSB) panel. OSB is more commonly used because of the absence of core voids in OSB (Section 14.7), which gives greater shear strength than a plywood web. Joints in the web are permissible, either in the form of butt joints or scarf joints.

I-joists are commonly used as floor joists, Figure 14.12, and roof rafters. They are dimensionally more stable than sawn lumber due to their plywood or OSB webs. (As we will see later in this chapter, atmospheric moisture changes do not affect plywood or OSB member dimensions as much as those of solid lumber.) That is why I-joist manufacturers claim that a floor constructed of I-joists is less prone to squeaking than one made of sawn lumber joists.

The most common flange width of I-joists is $1\frac{3}{4}$ in., with total depth ranging from 10 in. to 18 in., Figure 14.13. Most manufacturers supply the joists to their distributors and dealers in lengths of 60 ft, which are then cut to the lengths desired for the project.

Because there is less wood fiber in an I-joist, it is lighter than a corresponding sawn lumber joist. Less wood fiber means a more resource-efficient material. Another advantage of I-joists is that holes can be easily cut in webs to carry utility lines without compromising the structural capacity of the member. However, because of the proprietary and preengineered nature of the joists, manufacturers provide strict guidelines concerning the size, shape, and location of holes.

A disadvantage of I-joists is their thin web, which makes them relatively unstable. Hence, they must be braced during construction, that is, until the installation of floor or roof sheathing.

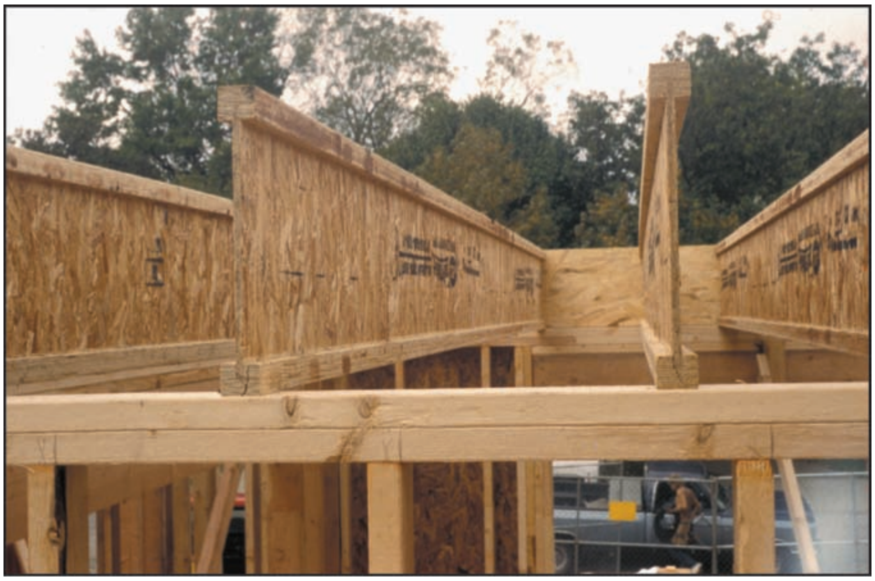


FIGURE 14.12 I-joists are commonly used as floor joists because of their greater dimensional stability and stiffness and their availability in longer lengths than solid sawn lumber joists.

Specifying I-Joists

Like the structural composite lumber industry, the wood I-joist industry is also proprietary. Each I-joist manufacturer formulates its own design by testing its products. Thus, the connection between the web and the flanges is proprietary, and so is the type of adhesive. Some of the commonly used flange-web connections are shown in Figure 14.14.

I-joist manufacturers provide ready-to-use span tables and other data to help design and construction professionals select the right types of joists for a project. All important construction details are also provided.

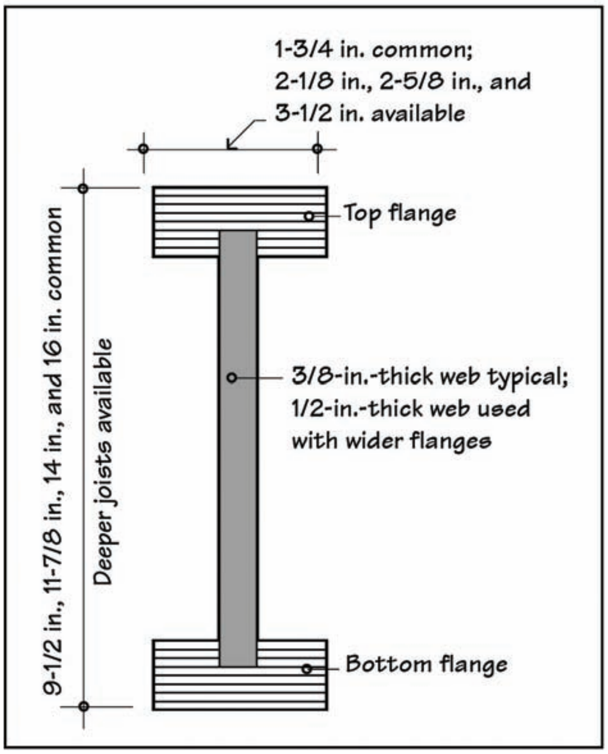


FIGURE 14.13 Commonly used dimensions of an I-joist. Manufacturers' literature must be consulted for exact dimensions.

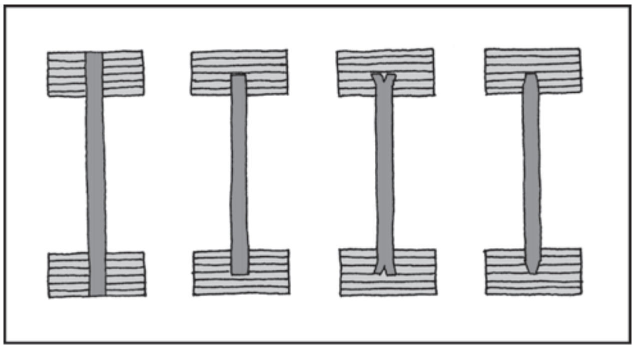


FIGURE 14.14 A few commonly used web-flange connections in I-joists.

14.4 WOOD TRUSSES

A truss consists of individual members that are joined together to form an array of interconnected triangular frames. Because a triangle is a naturally rigid geometric shape that resists being distorted when loaded from any direction, a truss is more rigid than a beam with the same amount of material. In fact, a truss is one of the most efficient means of carrying loads between supports. It is able to carry a greater load over a given span using less material than a rectangular beam or an I-beam. Figure 14.15 shows a typical wood truss, along with the important truss vocabulary.

Being made of individual triangles, truss members need not be continuous. Because the members are small in size, sawn lumber (generally 2 × 4 lumber) is most commonly used for trusses meant for residential or light commercial buildings. LVL, PSL, or glulam is also used by some manufacturers as members in trusses for heavy commercial or industrial applications.

In a sawn lumber truss, the individual members are connected together by metal nail plates, Figure 14.16(a). A nail plate is generally a 16-, 18-, or 20-gauge galvanized steel plate with the nails punched out of the sheet so that the nails and the plate are of one piece, Figure 14.16(b). The nails are generally $\frac{3}{8}$ in. long, with nearly eight nails per square inch. Nail plates are machine applied in manufacturing plants so that trusses are fully fabricated before they are transported to the construction site.

Several shapes, some of which are shown in Figure 14.17, are common for wood trusses. The shape and size of a truss are limited by manufacturing and transportation capabilities. Depending on its overall shape, a wood truss is one of the following:

- Roof truss
- Floor truss

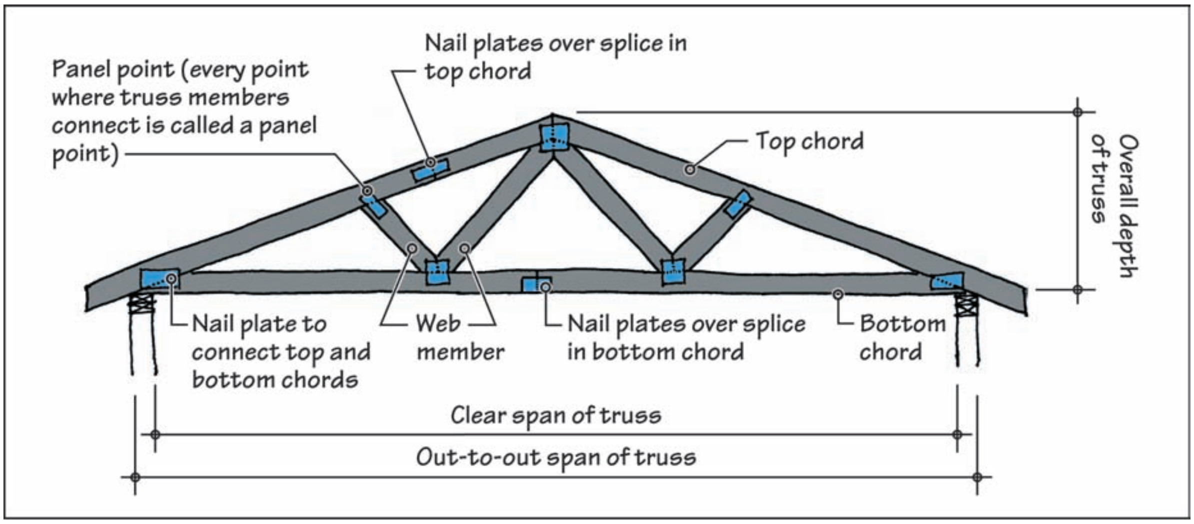

Panel point (every point where truss members connect is called a panel point)
Nail plates over splice in top chord
Top chord
Overall depth of truss
Nail plate to connect top and bottom chords
Web member
Nail plates over splice in bottom chord
Bottom chord
Clear span of truss
Out-to-out span of truss

FIGURE 14.15 Important terms related to trusses.

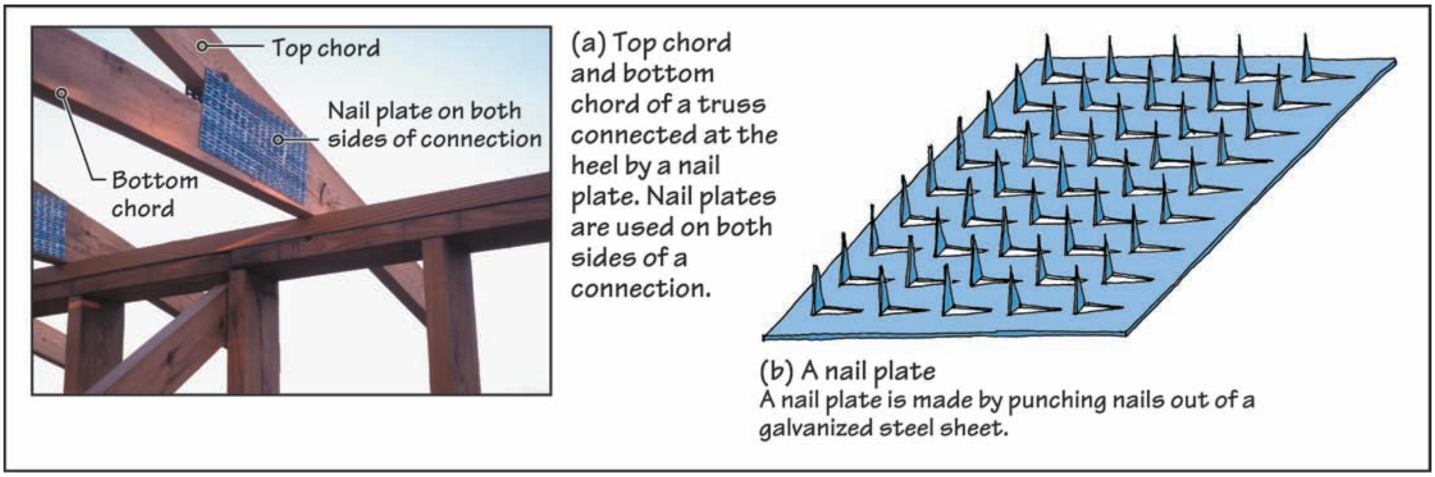

Top chord
Nail plate on both sides of connection
Bottom chord
(a) Top chord and bottom chord of a truss connected at the heel by a nail plate. Nail plates are used on both sides of a connection.
(b) A nail plate
A nail plate is made by punching nails out of a galvanized steel sheet.

FIGURE 14.16 Galvanized steel nail plate.

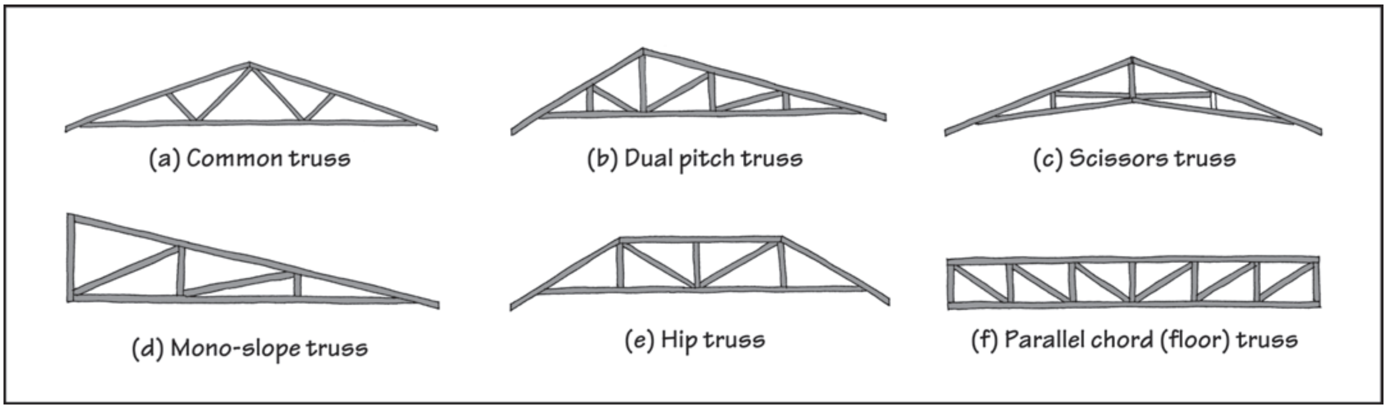

(a) Common truss
(b) Dual pitch truss
(c) Scissors truss
(d) Mono-slope truss
(e) Hip truss
(f) Parallel chord (floor) truss

FIGURE 14.17 Commonly used shapes of wood trusses for residential and light commercial structures.

ROOF TRUSSES

In a roof truss, the top chord is pitched. The bottom chord is generally horizontal, but it can be sloping, as in a scissors truss, Figure 14.17(c). Roof trusses are generally designed to bear on exterior walls, with the bottom chord providing the nailing surface for the ceiling. In other words, most interior walls of a building do not carry any roof loads. This is in contrast to the stick-built rafter and ceiling joist roof, in which the ceiling joists are generally supported on interior as well as exterior walls.

The use of roof trusses, therefore, gives greater freedom in the layout of interior walls and their future reconfiguration. Wood roof and floor trusses for residential and light commercial buildings are generally spaced 24 in. on center, Figure 14.18.

FLOOR TRUSSES

In a floor truss, the top chord is horizontal—parallel to the bottom chord. Thus, it is referred to as a *parallel chord truss*. Wood floor trusses are also called *trussed joists* because they function as floor joists, Figure 14.19. They are also used as lintel beams over openings, Figure 14.20. Trussed joists can be provided with a rectangular opening in the middle of the joist for mechanical ducts, Figure 14.21.

The versatility and cost effectiveness of trussed joists make them a popular choice in wood buildings with long spans (greater than 20 ft). A disadvantage of trussed joists (also of roof trusses) is that they cannot be cut to size. In other words, their use does not permit last-minute changes in design.

In addition to all-wood joists, wood-metal joists are available, in which the web members are made of hollow steel pipes and the chords are made of LVL or sawn lumber, Figure 14.22. They are generally used in industrial buildings, where the loads are greater and the spans are longer. The use of steel in webs increases the strength and stiffness of the joists, and the wood chords provide a nailable surface for roof and floor sheathing and the ceiling.

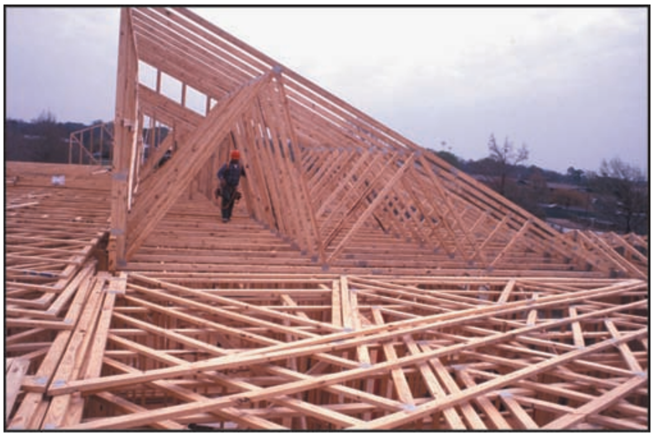


FIGURE 14.18 Mono-slope roof trusses. Two mono-slope trusses laid end-to-end and field connected make a common roof truss. Mono-slope trusses are generally used where a common truss is too large to transport to the site. Wood trusses are generally spaced 24 in. on center.

SPECIFYING WOOD TRUSSES

When using trusses for a project, all that an architect, engineer, or builder has to do is to determine the load requirements, shape, span, and slope. The truss manufacturer then determines the detailed truss geometry, sizes of truss members, wood species, and so on. The truss fabricator prepares shop drawings for the trusses and sends them to the engineer, architect, or builder for approval.

Installing trusses on the site is as important as truss design or fabrication. A crane or other lifting equipment (e.g., fork lift) is generally required, and installers must be skilled and experienced. During erection, wood trusses should almost always be held in an upright position—in the position in which they are to be used in the building, Figure 14.23.

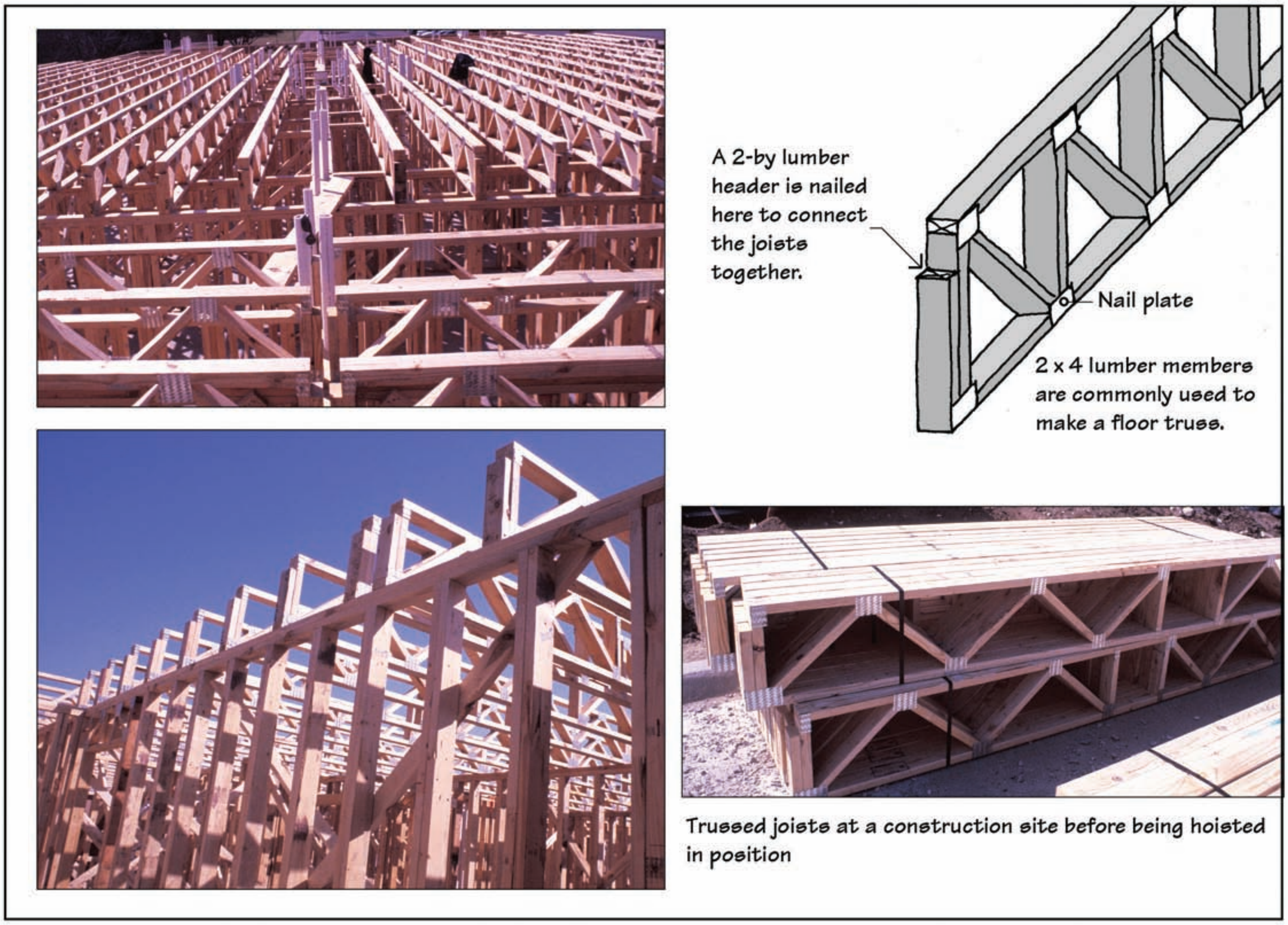

A 2-by lumber header is nailed here to connect the joists together.
Nail plate
2 x 4 lumber members are commonly used to make a floor truss.
Trussed joists at a construction site before being hoisted in position

FIGURE 14.19 Floor trusses (trussed joists).

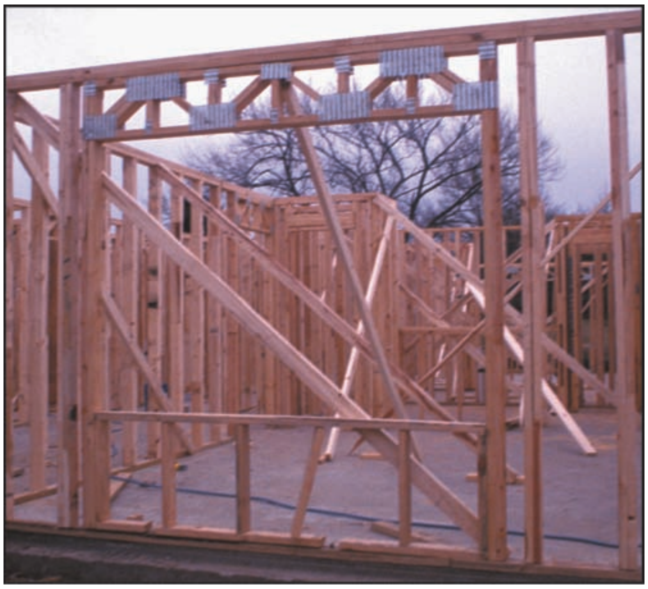


FIGURE 14.20 Trussed lintel over an opening.

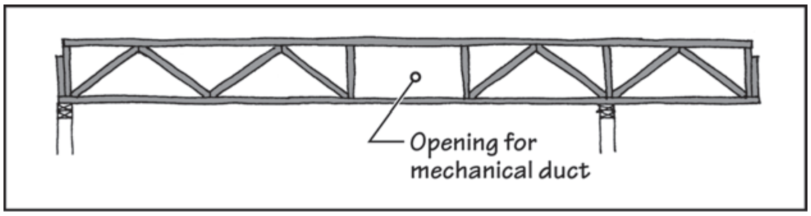

Opening for mechanical duct

FIGURE 14.21 A floor truss with a rectangular opening to accommodate a mechanical duct.

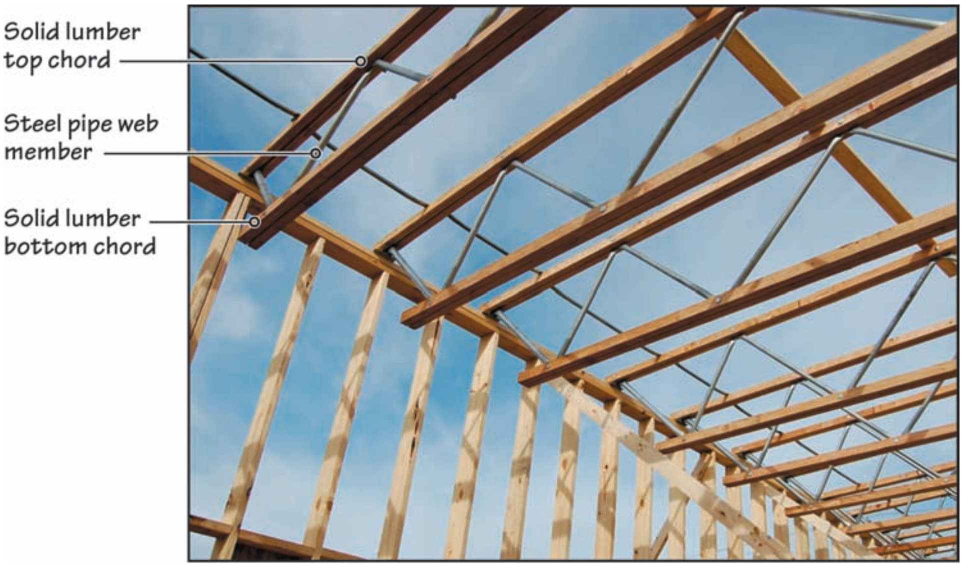

Solid lumber top chord
Steel pipe web member
Solid lumber bottom chord

FIGURE 14.22 Wood-steel trussed joists.

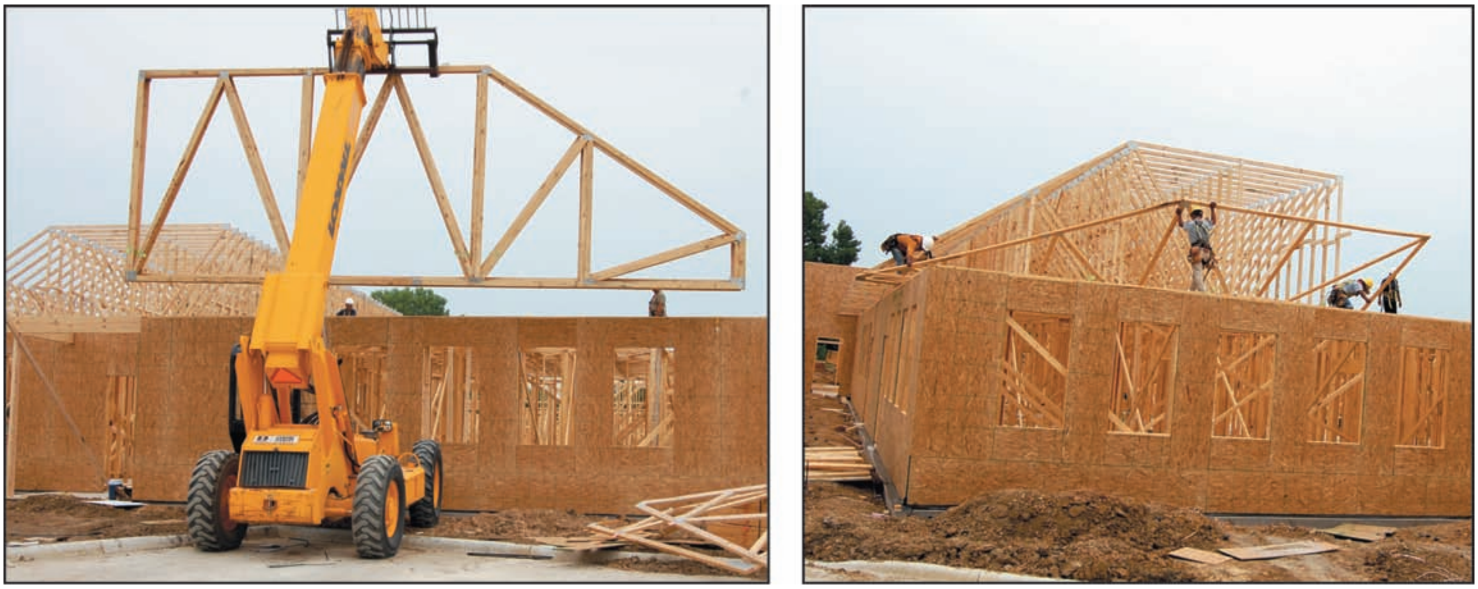


FIGURE 14.23 Because wood trusses are made from thin (2-by) members and connected together with (sheet steel) nail plates, they must be handled carefully during hoisting or placing in position so that the nail-plate connected joints do not open up. That is why, as shown in this figure, a roof truss is being carried in vertical alignment by a fork lift.

When held horizontally, the lateral bending of truss members during lifting may overstress the connections, causing nail plates to loosen or pop out.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The most common use of glulam members is in
- **a.** structural panels.
- **b.** long-span beams.
- **c.** short-span beams.
- **d.** none of the above.

2. Unprotected glulam members with a large cross section are considered to provide a fire resistance rating of up to
- **a.** $\frac{1}{2}$ h.
- **b.** 1 h.
- **c.** 2 h.
- **d.** 3 h.
- **e.** 4 h.

3. A glulam member
- **a.** must be made using long, continuous lengths of high-grade sawn lumber.
- **b.** is generally stronger and stiffer than sawn lumber of the same dimensions.
- **c.** requires complete protection from exterior elements due to its water-soluble adhesive.
- **d.** none of the above.
- **e.** all of the above.

4. Unbalanced beams can be used only as single-span beams.
- **a.** True
- **b.** False

5. Balanced glulam beams are mandated for
- **a.** continuous beams.
- **b.** single-span beams.
- **c.** beams with an overhang.
- **d.** (a) and (c).
- **e.** (b) and (c).

6. Laminated veneer lumber (LVL) is
- **a.** produced by gluing together wood veneers that are approximately $\frac{1}{8}$ in. thick.
- **b.** generally used as floor joists and beams.
- **c.** glued with all veneers running in the same direction.
- **d.** stronger along the grain and weaker across the grain.
- **e.** all of the above.

7. Wood I-joists are made of LVL or solid sawn lumber flanges and webs.
- **a.** True
- **b.** False

8. Compared to sawn lumber joists, wood I-joists are
- **a.** less expensive.
- **b.** slightly heavier.
- **c.** dimensionally more stable.
- **d.** all of the above.

9. Characteristics of a truss include
- **a.** greater spanning capability than a sawn lumber beam having the same amount of material.
- **b.** individual members joined together to form an array of interconnected rectangular frames.
- **c.** individual members joined together to form an array of interconnected triangular frames.
- **d.** (a) and (b).
- **e.** (a) and (c).

10. Nail plates, used to join members of a truss, are generally used only on one face of the truss.
- **a.** True
- **b.** False

11. Wood trusses are generally spaced at
- **a.** 12 in. on center.
- **b.** 24 in. on center.
- **c.** 48 in. on center.
- **d.** 60 in. on center.

14.5 WOOD PANELS

Wood panels are an important part of wood frame construction. They are used structurally— as floor sheathing, roof sheathing, and wall sheathing—and nonstructurally—as exterior siding and interior paneling. Wood panels are divided into two types:

- *Veneered panels*—consisting of plywood panels.
- *Nonveneered panels*—consisting of oriented strandboard (OSB) and particle board panels. Particle board panels are generally used in shelving and furniture making and are not discussed here.

14.6 PLYWOOD PANELS

Plywood panels are made by gluing wood veneers under heat and pressure. Veneers are generally produced by a machine that holds a debarked log at two ends in a lathe and rotates the log against a stationary knife blade extending throughout the length of the log, Figure 14.24. This operation peels the log off, giving a continuous veneer about $\frac{1}{8}$ in. thick, in much the same way that one would unroll a paper towel. The veneer so obtained is subsequently cut to desired sizes.

To make a plywood panel, the defects in veneers, such as knot holes and splits, are cut away or repaired where necessary. The veneers are then dried and glued together so that the grain direction in each veneer is oriented at a right angle to the grain direction of the adjacent veneer, Figure 14.25.

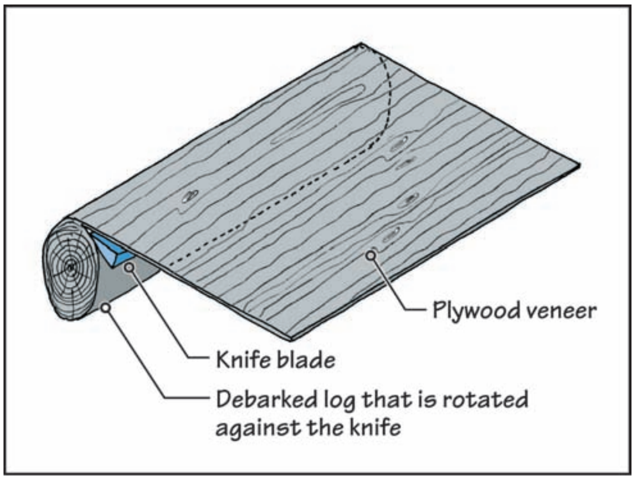
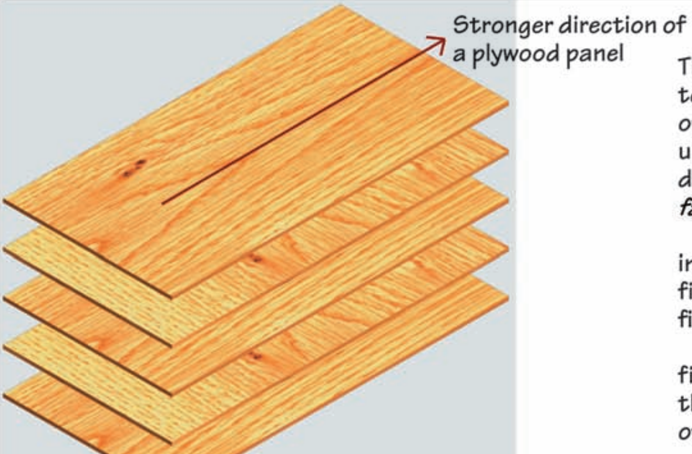


FIGURE 14.24 Rotary slicing of a log—a commonly used method of making plywood veneers.


Stronger direction of a plywood panel

The grain directions in alternate veneer layers are at right angles to each other. Generally, this arrangement implies an odd number of veneers in a panel. However, an even number of veneers is also used in which the two innermost veneers are oriented in the same direction so that the top and bottom veneers (referred to as ***face veneers***) are always in the same direction.

For example, if a panel is made of six veneers, of which the two innermost veneers are in the same direction, it is referred to as a five- layer, six-veneer panel. The panel shown here is a five-layer, five-veneer panel.

Because bending stresses maximize at the top and bottom fibers in a panel and because wood is stronger along the grain than across the grain, a plywood panel is stronger in the direction of the grain of the face veneers.

FIGURE 14.25 Orientation of veneer grains in a plywood panel.

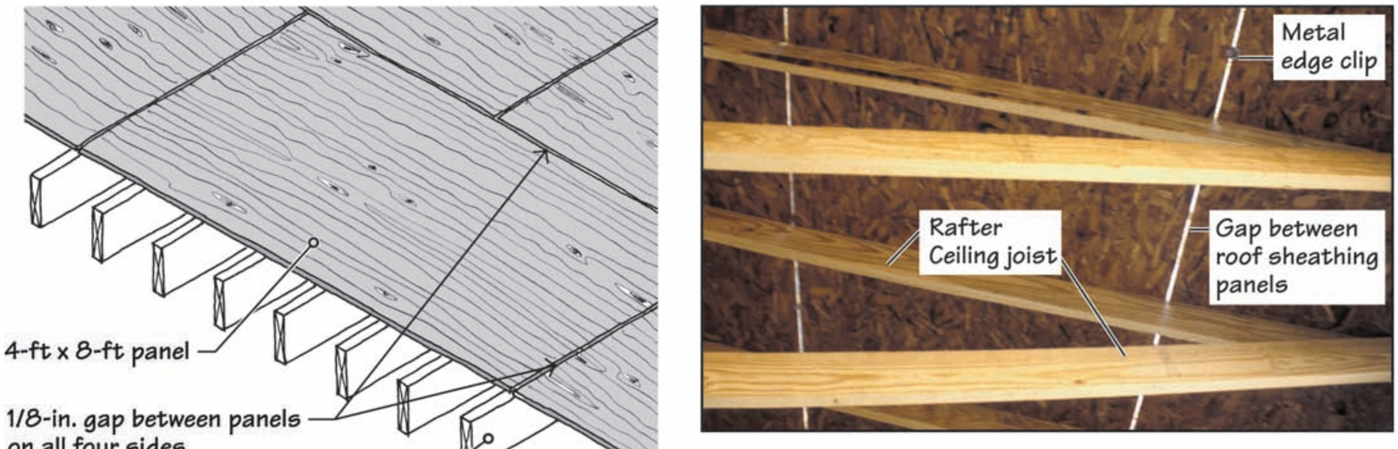
Because wood is stronger along the grain than across the grain, cross-graining tends to equalize the strength of a plywood panel in its two principal directions. It also makes a plywood panel dimensionally more stable because shrinkage and swelling of wood are high across the grain and negligible along the grain. For the same reason, a plywood panel is less likely to split than sawn lumber. Therefore, it can be nailed near its edge without splitting.

The most commonly used plywood panel size is 4 ft × 8 ft, with thickness varying from $\frac{1}{4}$ in. to 1 in. Longer plywood panels are manufactured for siding and industrial use. The panel dimension of 4 ft × 8 ft is its nominal dimension. Its actual dimension is $\frac{1}{8}$ in. smaller in length as well as in width. In other words, the actual dimensions of a 4-ft × 8-ft panel are $47\frac{7}{8}$ in. × $95\frac{7}{8}$ in. This allows a panel to be installed with a $\frac{1}{8}$-in. space all around for moisture expansion, Figure 14.26.

The grain direction of face veneers of a panel is oriented along the panel's length (along the 8-ft dimension in a 4-ft × 8-ft panel), making the panel stronger in its long direction. In structural applications, the long direction of a plywood panel should, therefore, be perpendicular to the supporting joists or rafters.

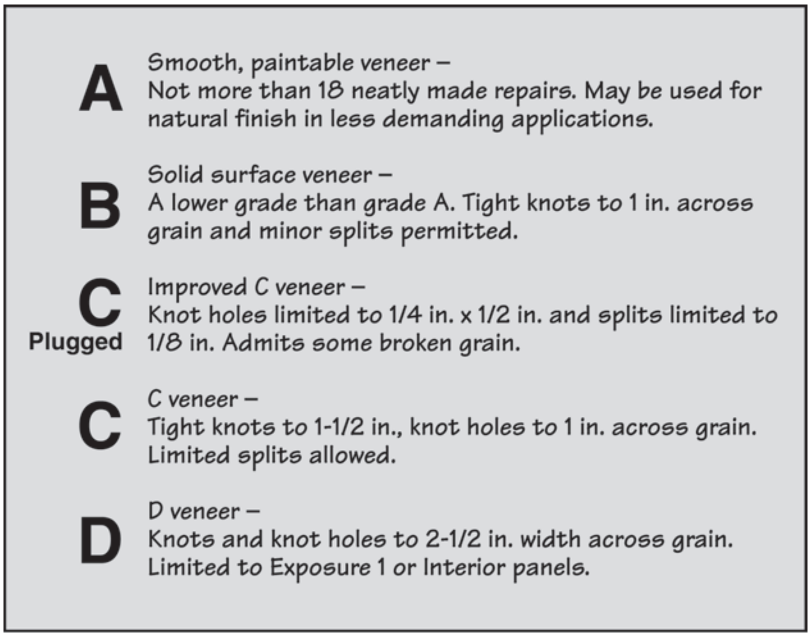
VENEER GRADES OF SOFTWOOD PLYWOOD

Plywood veneers used in building construction are generally obtained from softwoods. Softwood veneers are graded in five grades—A, B, C-plugged, C, and D—based on the type and size of defects such as knots and splits, Figure 14.27. Veneer grade A is the highest grade,


4-ft x 8-ft panel
1/8-in. gap between panels on all four sides
Floor joist or rafter
Metal edge clip
Rafter
Ceiling joist
Gap between roof sheathing panels

1/8-in. gap between roof sheathing panels. The white line in this photo represents daylight coming through the gap. Note that roof sheathing requires (metal) edge clips between adjacent panels to add to their continuity.

FIGURE 14.26 Plywood panels must be oriented with their long direction perpendicular to the supporting members. Additionally, a gap of nearly $\frac{1}{8}$ in. must be left all around panels to accommodate moisture expansion.



Grade	Description
A	Smooth, paintable veneer – Not more than 18 neatly made repairs. May be used for natural finish in less demanding applications.
B	Solid surface veneer – A lower grade than grade A. Tight knots to 1 in. across grain and minor splits permitted.
C Plugged	Improved C veneer – Knot holes limited to 1/4 in. x 1/2 in. and splits limited to 1/8 in. Admits some broken grain.
C	C veneer – Tight knots to 1-1/2 in., knot holes to 1 in. across grain. Limited splits allowed.
D	D veneer – Knots and knot holes to 2-1/2 in. width across grain. Limited to Exposure 1 or Interior panels.

FIGURE 14.27 A brief description of plywood veneer grades.

and veneer grade D is the lowest. Thus, in veneer grade D, the number of knot holes and their sizes are higher than in any other grade.

SANDED, UNSANDED, AND TOUCH-SANDED PLYWOOD PANELS

The veneer grade on plywood panel faces is generally different from the veneer grades in the panel's core. Additionally, panels meant to be exposed on one side only may have a high veneer grade on one face and a lower grade on the other face. For example, a panel may be an A-C plywood panel, which indicates that one face of the panel has grade A veneer and the other face has grade C veneer.

Plywood panels with grade A or B face veneers are always sanded smooth because such panels are generally used in cabinet work, furniture work, and shelving. Panels with C-plugged, C, and D face veneers are touch-sanded to provide a more uniform panel thickness. Panels used for sheathing purposes are unsanded.

14.7 OSB PANELS

For many years, plywood panels were the only wood panels available. Recently, as a result of the desire to use resources more efficiently, technology has been developed to use shredded, wafer-thin wood strands, compressed and glued to form a panel. Panels made with wood strands are called *oriented-strandboard* (OSB) panels because alternate layers of strands are oriented at right angles to each other in the same way as the veneers in a plywood panel.

OSB panels are made by gluing several layers of wood strands under heat and pressure, Figure 14.28. They are generally made to the same dimensions as plywood panels. Like plywood, the most commonly used OSB panel is 4 ft × 8 ft (nominal) and is stronger along its long direction.

NOTE

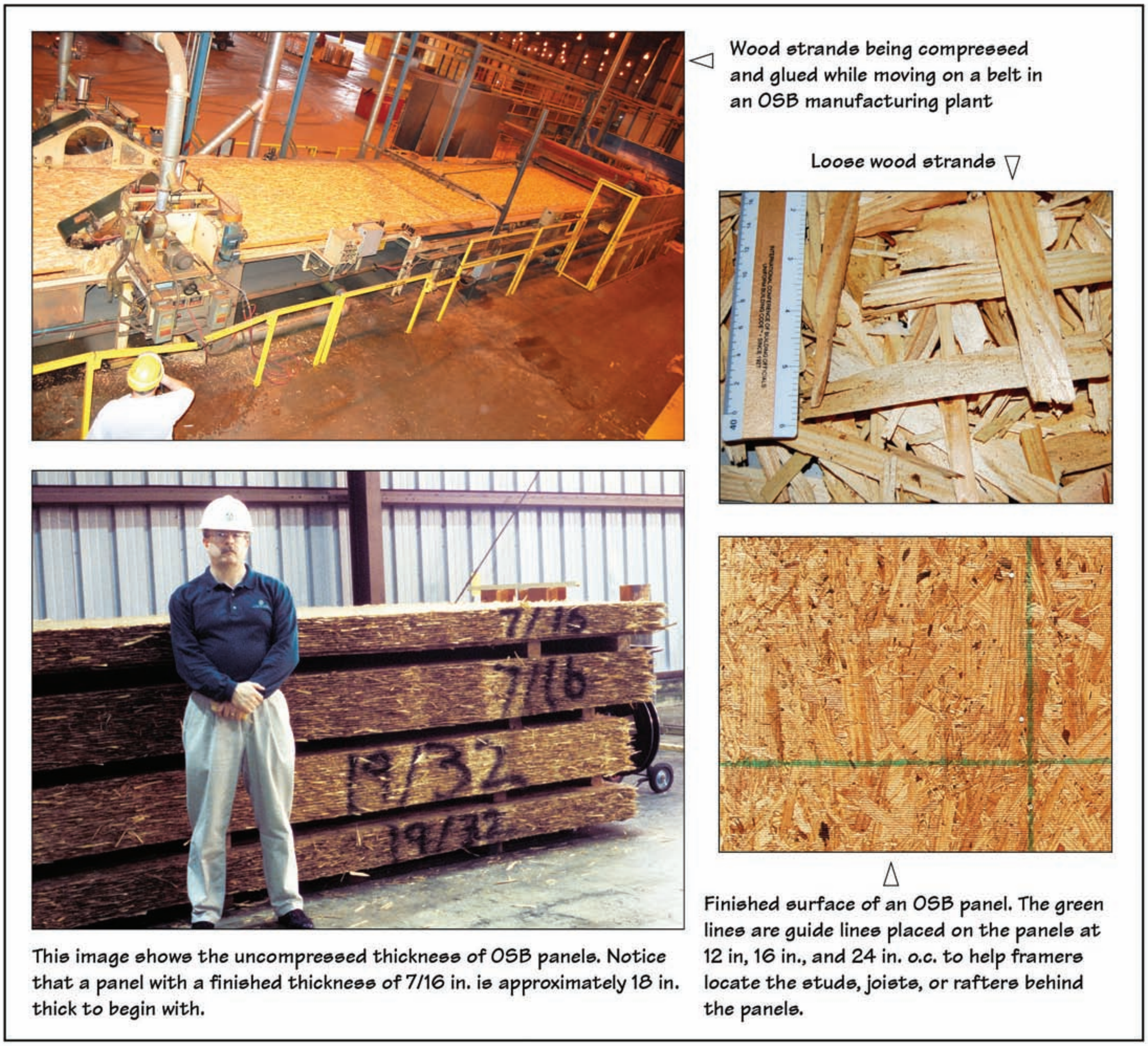
Versatility of OSB Panels

For all structural sheathing (wall sheathing, floor sheathing, and roof sheathing), OSB is currently the material of choice. The use of plywood in floor and roof sheathing declined from nearly 90% in 1978 to 26% in 1999 in favor of OSB (Bruce Smith, 2001 President, National Association of Home Builders, in *Builder and Developer Magazine*, 2001, an online magazine (bdmag.com)). Similarly, the use of paper-faced gypsum wall sheathing has virtually disappeared and has been replaced by OSB sheathing in residential construction.

OSB VERSUS PLYWOOD

Because OSB generally costs less than plywood, it has become the material of choice for sheathing a wood frame building. OSB provides higher shear strength (racking resistance) than plywood because of the absence of core voids. (The lower shear strength in plywood panels is due to the presence of knot holes and splits in veneers.) Thus, it is not uncommon to see OSB panels used for floor sheathing, roof sheathing, and wall sheathing in a typical wood frame building, Figure 14.29.

However, OSB panels have a few limitations. Plywood panels, particularly those with higher grades on face veneers, can be stained or painted. This is not true of OSB panels, which are intended only for structural applications. They generally cannot be sanded smooth like plywood panels. OSB panels are also prone to edge swelling if they remain wet for prolonged periods. Additionally, OSB panels cannot be treated with preservatives, whereas preservative-treated plywood is available.



Wood strands being compressed and glued while moving on a belt in an OSB manufacturing plant

Loose wood strands

This image shows the uncompressed thickness of OSB panels. Notice that a panel with a finished thickness of 7/16 in. is approximately 18 in. thick to begin with.

Finished surface of an OSB panel. The green lines are guide lines placed on the panels at 12 in, 16 in., and 24 in. o.c. to help framers locate the studs, joists, or rafters behind the panels.

FIGURE 14.28 OSB panel manufacturing.

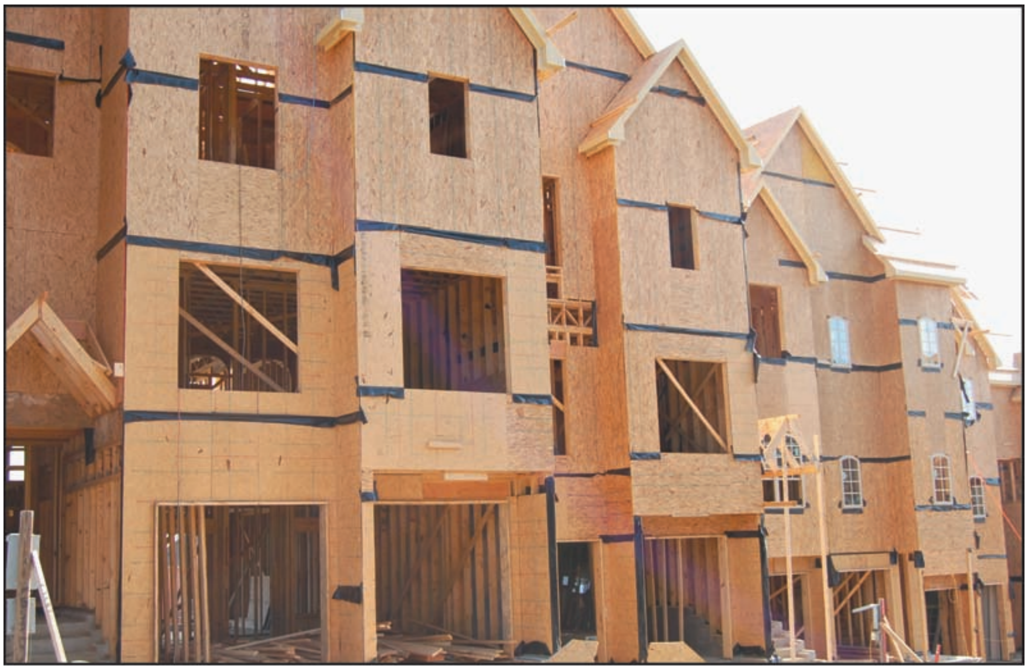


FIGURE 14.29 Because of their lower cost and greater racking resistance, OSB panels are generally used to sheath the entire envelope of a wood frame building (see also Chapter 15, Section 15.9).

14.8 SPECIFYING WOOD PANELS—PANEL RATINGS

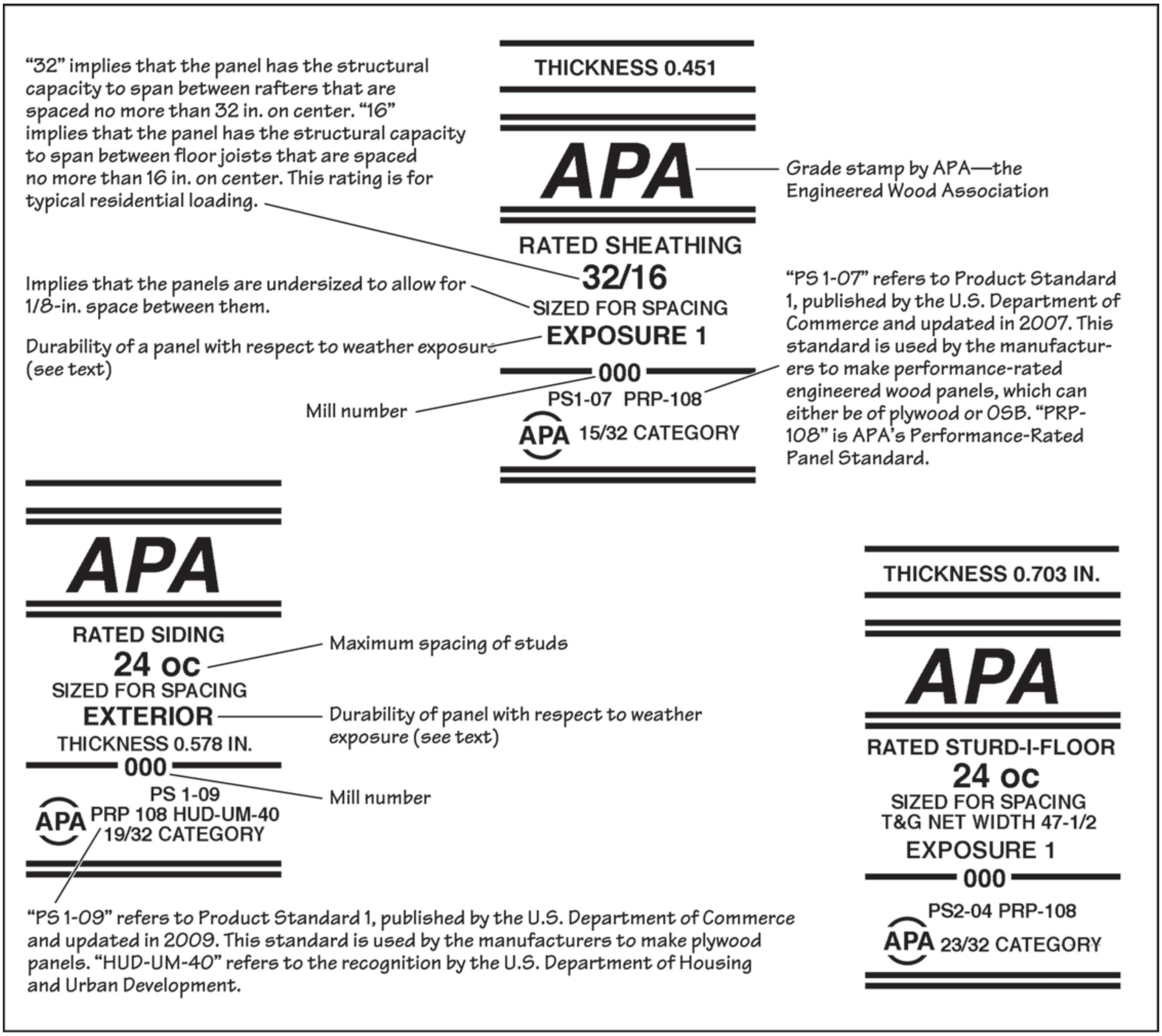
Wood panels can be divided into two categories based on their end use:

- Performance-rated engineered wood panels
- Sanded and touch-sanded plywood panels

PERFORMANCE-RATED ENGINEERED WOOD PANELS

Performance-rated engineered wood panels are meant for structural applications (e.g., wall sheathing, floor sheathing, and roof sheathing) as well as for nonstructural use in exterior siding. The panels are preengineered and rated accordingly. The rating provides the user with the panel's structural capacity and other performance data, such as its intended end use and durability. This simplifies the specification of the panel and relieves the user of any further investigation.

Performance rating means that as long as the panel meets the specified requirements for end use (exposure durability and span rating), it does not matter which material—plywood or OSB—it is made of. The rating is achieved through a third-party certification process and stamped accordingly. Typical ratings (grade stamps) of panels are given in Figure 14.30. The following performance properties are of particular importance:


THICKNESS 0.451
APA
RATED SHEATHING
32/16
SIZED FOR SPACING
EXPOSURE 1
000
PS1-07 PRP-108
APA 15/32 CATEGORY
APA
RATED SIDING
24 oc
SIZED FOR SPACING
EXTERIOR
THICKNESS 0.578 IN.
000
PS 1-09
APA PRP 108 HUD-UM-40
19/32 CATEGORY
THICKNESS 0.703 IN.
APA
RATED STURD-I-FLOOR
24 oc
SIZED FOR SPACING
T&G NET WIDTH 47-1/2
EXPOSURE 1
000
PS2-04 PRP-108
APA 23/32 CATEGORY

"32" implies that the panel has the structural capacity to span between rafters that are spaced no more than 32 in. on center. "16" implies that the panel has the structural capacity to span between floor joists that are spaced no more than 16 in. on center. This rating is for typical residential loading.

Grade stamp by APA—the Engineered Wood Association

Implies that the panels are undersized to allow for 1/8-in. space between them.

Durability of a panel with respect to weather exposure (see text)

Mill number

"PS 1-07" refers to Product Standard 1, published by the U.S. Department of Commerce and updated in 2007. This standard is used by the manufacturers to make performance-rated engineered wood panels, which can either be of plywood or OSB. "PRP-108" is APA's Performance-Rated Panel Standard.

Maximum spacing of studs

Durability of panel with respect to weather exposure (see text)

Mill number

"PS 1-09" refers to Product Standard 1, published by the U.S. Department of Commerce and updated in 2009. This standard is used by the manufacturers to make plywood panels. "HUD-UM-40" refers to the recognition by the U.S. Department of Housing and Urban Development.

FIGURE 14.30 Typical APA grade stamps on performance-rated engineered wood panels. TECO, another grading agency, uses similar stamps.

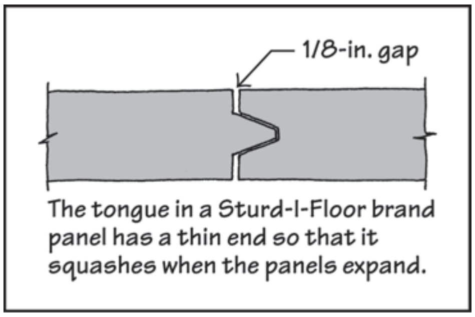

1/8-in. gap
The tongue in a Sturd-I-Floor brand panel has a thin end so that it squashes when the panels expand.

FIGURE 14.31 Tongue-and-groove joint between Sturd-I-Floor panels.

NOTE

Sturd-I-Floor as Combination Floor Sheathing

APA-rated Sturd-I-Floor is a commonly specified floor sheathing, ranging in thickness from $\frac{3}{4}$ in. to $1\frac{1}{8}$ in. It does not require any underlayment and is commonly used in situations where carpet is the required floor finish. According to APA, the panel surface of Stud-I-Floor has extra resistance to punch-through damage.

Intended End Use Performance-rated panels can be used in one of the following three situations:

- Sheathing (over studs, floor joists, or rafters)
- Combination floor sheathing
- Exterior siding

Combination floor sheathing is a special type of floor sheathing that replaces a two-layer covering over floor joists. If regular (square-edged) sheathing is used over floor joists, it requires an additional layer of panels over the sheathing panels. The additional panel layer is called *underlayment* because it functions as an underlayer for the floor finish and is typically $\frac{1}{4}$-in.-thick sanded plywood or hardboard.

Combination floor sheathing panels have been developed to act as sheathing as well as underlayment and are generally provided with a tongue-and-groove (T&G) profile along the long (8-ft) edges, Figure 14.31, although square-edged panels are also available.

Whereas sheathing and combination sheathing panels may be of plywood or OSB, only plywood is used in exterior siding panels for aesthetic and durability reasons.

Exposure Durability: Engineered wood panels are produced in two exposure-durability classifications:

- Exterior
- Exposure 1

Exterior-rated panels are designed for permanent exposure to the weather—to withstand the effect of rain, humidity, and sunshine. *Exposure 1* panels are meant for use in protected situations, that is, where the panels are to be covered with an exterior facing material. However, Exposure 1 panels are designed to withstand the effect of weather for several days due to construction delays. Both Exterior and Exposure 1 panels use the same waterproof glue. The difference lies in the panels' composition. That is why OSB panels are not available as Exterior grade panels because of edge swelling and related problems.

Note that the exposure-durability classification of panels relates to the moisture resistance of the glue bond, not the fungal resistance of the panel. Thus, an Exterior-rated panel, if not used correctly, is subject to fungal attack.

Span Rating and Overall Thickness: As stated previously, performance-rated panels are preengineered, which means that architects, engineers, and builders do not need to calculate the load capacity of the panel. This information is provided by the manufacturer and is stamped on the panel, along with the panel's end use, exposure classification, and thickness.

SANDED AND TOUCH-SANDED PLYWOOD PANELS

Sanded and touch-sanded plywood panels are rated for performance as well as exterior appearance. The exterior appearance refers to the grade of face veneers of the panels. A few typical grade stamps of such panels are shown in Figure 14.32. Note that the performance-rated panels are rated only for performance, not for appearance.

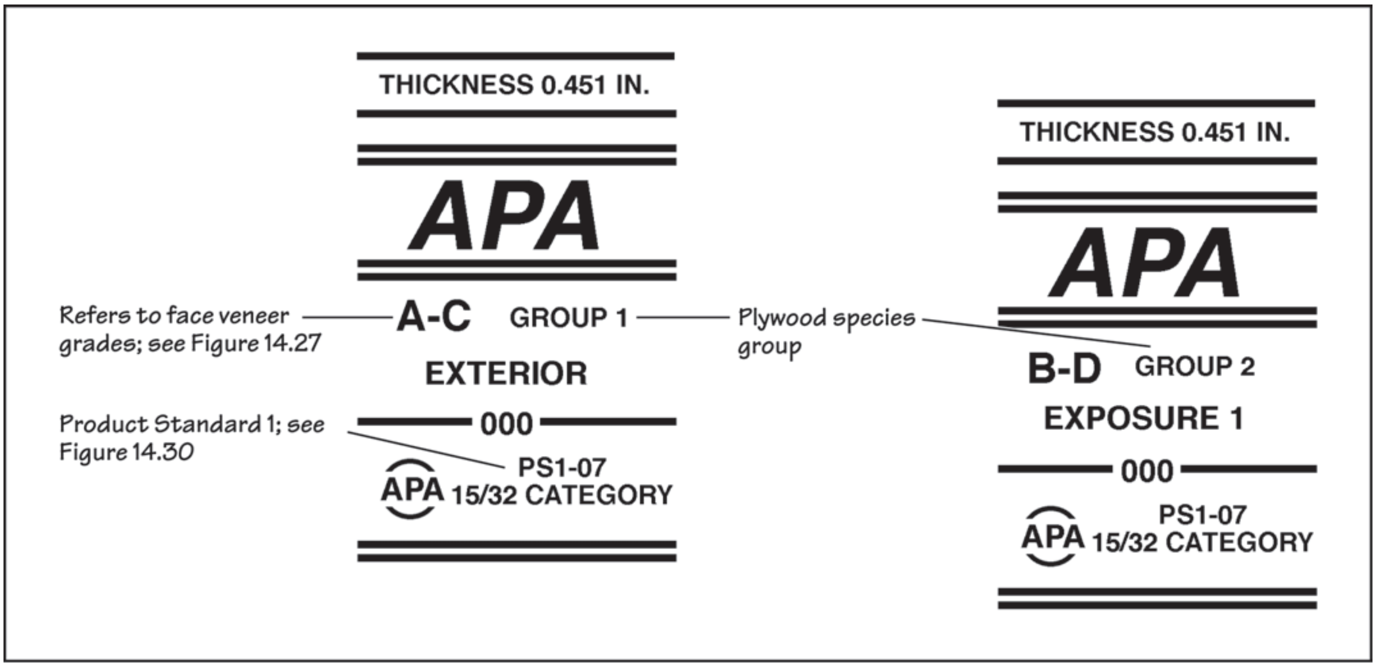

THICKNESS 0.451 IN.
APA
A-C GROUP 1
EXTERIOR
000
APA PS1-07 15/32 CATEGORY
Refers to face veneer grades; see Figure 14.27
Product Standard 1; see Figure 14.30
Plywood species group
THICKNESS 0.451 IN.
APA
B-D GROUP 2
EXPOSURE 1
000
APA PS1-07 15/32 CATEGORY

FIGURE 14.32 Typical grade stamps on sanded and touch-sanded plywood panels.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

12. Plywood panels are made by gluing under heat and pressure layers of
- **a.** wood veneers so that the wood grain in all layers is in the same direction.
- **b.** wood veneers so that the wood grains in adjacent layers are perpendicular to each other.
- **c.** shredded wood strands so that the strands in all layers are in the same direction.
- **d.** shredded wood strands so that the strands in adjacent layers are perpendicular to each other.

13. Cross-graining makes a plywood panel
- **a.** dimensionally more stable.
- **b.** less likely to split than solid sawn lumber.
- **c.** stronger in the direction of face veneer grains.
- **d.** all of the above.
- **e.** (a) and (c).

14. The most commonly used plywood panel (nominal) size is 4 ft × 8 ft.
- **a.** True
- **b.** False

15. Plywood panels should be placed with their longer dimension
- **a.** parallel to rafters or joists.
- **b.** perpendicular to rafters or joists.
- **c.** diagonal to rafters or joists.
- **d.** either (a) or (b).
- **e.** either (a) or (c).

16. With respect to veneer quality, softwood plywood is graded in grades
- **a.** A to C.
- **b.** B to D.
- **c.** A to D.
- **d.** A to E.
- **e.** B to F.

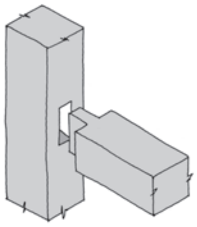
17. An OSB panel generally has greater shear strength than a plywood panel of the same size and thickness.
- **a.** True
- **b.** False

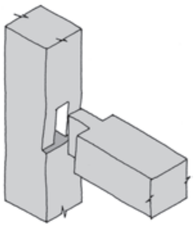
18. Grade stamps on engineered wood panels specify
- **a.** intended use and exposure.
- **b.** allowable spans.
- **c.** mill number.
- **d.** thickness.
- **e.** all of the above.

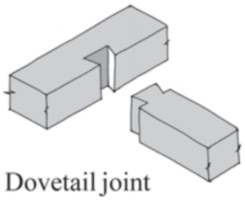
19. Exterior siding panels may be made of OSB or plywood.
- **a.** True
- **b.** False

14.9 FASTENERS FOR CONNECTING WOOD MEMBERS

The traditional method of connecting wood members was through different types of interlocking joints, such as a mortise-and-tenon joint, housed mortise-and-tenon joint, and dovetail joint. Except for fine furniture and to some extent in timber frame construction (see the Expand Your Knowledge section at the end of Chapter 15), these *joinery-methods*, as they are referred to, have been replaced by simpler and more effective methods that often yield stronger connections. Most joints in contemporary wood construction are made by simply nailing the members together or by nailing them through sheet metal connectors. In some joints, adhesives are used in addition to nails, whereas in others, screws and bolts are necessary.


Mortise-and-tenon joint


Housed mortise-and-tenon joint


Dovetail joint

TYPES OF NAILS

A nail is generally made of low- or medium-carbon steel wire that is heat treated to increase its stiffness. Where increased impact resistance is needed, such as for masonry nails, steel with a higher carbon content is used. Nails made in this way without any further treatment for corrosion are called *brite nails*. In exterior siding and decks where greater corrosion resistance is needed, hot-dip galvanized nails are used. (Stainless steel nails can provide even higher corrosion resistance but are expensive.)

For increased holding power, nails are phosphate or vinyl coated. Vinyl-coated nails produce heat due to friction when the nail is driven, melting the vinyl, which increases the bond between the wood and the nail. They have a thinner shank and are easier to drive into wood and are, therefore, called *sinker nails*. For most structural connections, however, brite (ungalvanized, uncoated) steel nails are used.

A nail has three basic parts: (a) the tip, (b) the shank, and (c) the head, Figure 14.33. The tip of most nails is diamond shaped. Therefore, the nail type is distinguished by the type of its head and the type of shank. Some of the commonly used nail types in wood frame construction are shown in Figure 14.34.

For framing connections, common nails are most frequently used. Box nails are similar to common nails but have a thinner shank, which reduces wood splitting. They are generally used for attaching wood shingles. Casing nails and finish nails are used for finish carpentry. Deformed shank nails are used for attaching wood flooring or gypsum wallboard.

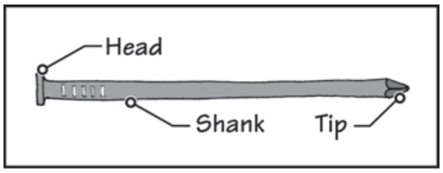


FIGURE 14.33 Parts of a nail.

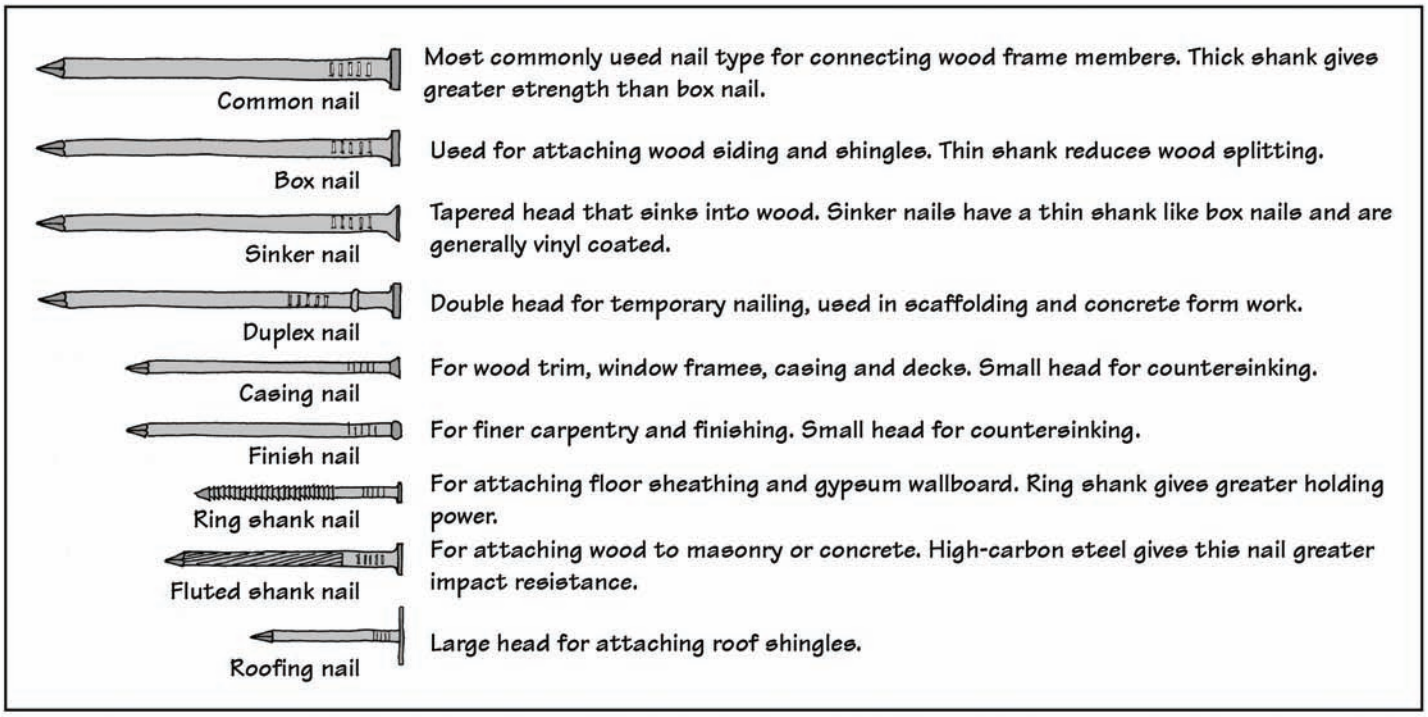
NAIL SIZES

The length of common nails in the United States is specified by a *penny* (abbreviated as *d*) designation. For example, a 10d nail (called *a 10 penny nail*) is 3 in. long. The penny designation originated in England centuries ago when 1 pound weight of 10d nails cost 10 pence, 1 pound weight of 12d nails cost 12 pence, and so on.

Common nails are available in lengths ranging from 2d to 60d. A 2d nail is 1 in. long, and a 60d nail is 6 in. long. From 2d to 10d, the increase in length is $\frac{1}{4}$ in. per penny. Therefore, a 10d nail is 3 in. long. The next two nail sizes are 12d and 16d, with lengths of $3\frac{1}{4}$ in. and $3\frac{1}{2}$ in., respectively. A 20d nail is 4 in. long, Figure 14.35. Most commonly used nail sizes in wood frame construction are 6d, 8d, 10d, and 16d, highlighted in Figure 14.35.

NAILED CONNECTIONS

Nails work best when they are subjected to shear—that is, when the load is perpendicular to the length of the nails—or when they are in compression. Nails are particularly weak in withdrawal. Withdrawal resistance is needed when the load is parallel to the length of the


Common nail
Box nail
Sinker nail
Duplex nail
Casing nail
Finish nail
Ring shank nail
Fluted shank nail
Roofing nail

Most commonly used nail type for connecting wood frame members. Thick shank gives greater strength than box nail.

Used for attaching wood siding and shingles. Thin shank reduces wood splitting.

Tapered head that sinks into wood. Sinker nails have a thin shank like box nails and are generally vinyl coated.

Double head for temporary nailing, used in scaffolding and concrete form work.

For wood trim, window frames, casing and decks. Small head for countersinking.

For finer carpentry and finishing. Small head for countersinking.

For attaching floor sheathing and gypsum wallboard. Ring shank gives greater holding power.

For attaching wood to masonry or concrete. High-carbon steel gives this nail greater impact resistance.

Large head for attaching roof shingles.

FIGURE 14.34 Commonly used types of nails in wood frame construction.

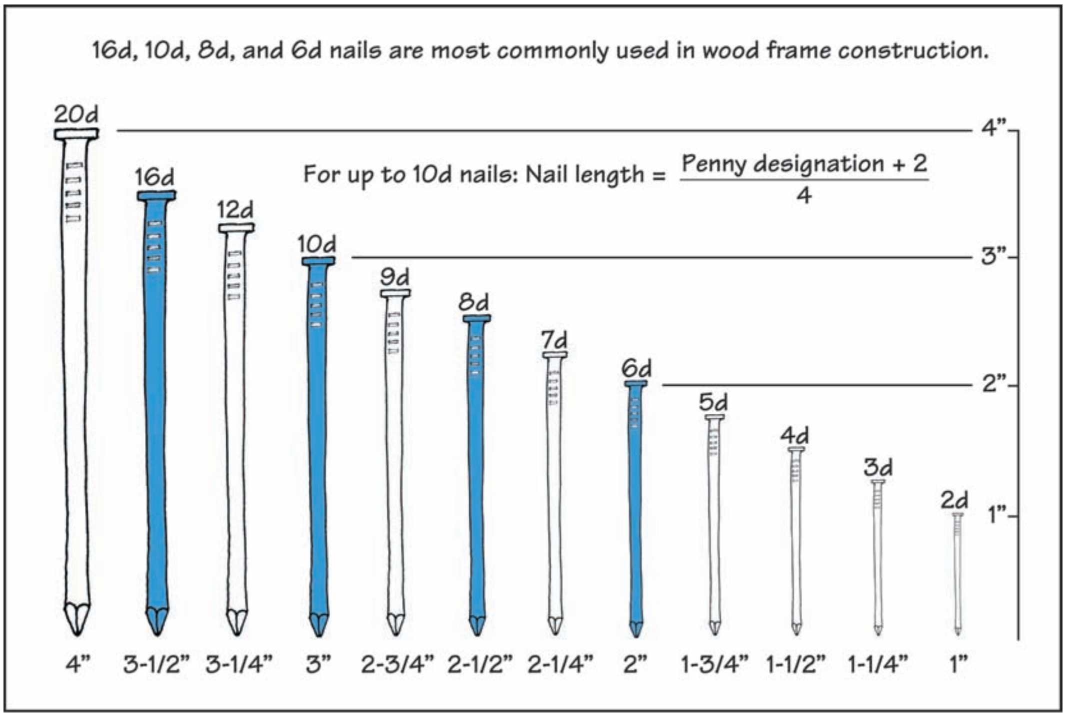

16d, 10d, 8d, and 6d nails are most commonly used in wood frame construction.
For up to 10d nails: Nail length = Penny designation + 2 / 4
20d
16d
12d
10d
9d
8d
7d
6d
5d
4d
3d
2d
4"
3"
2"
1"
4"
3-1/2"
3-1/4"
3"
2-3/4"
2-1/2"
2-1/4"
2"
1-3/4"
1-1/2"
1-1/4"
1"

FIGURE 14.35 Standard lengths of common nails.

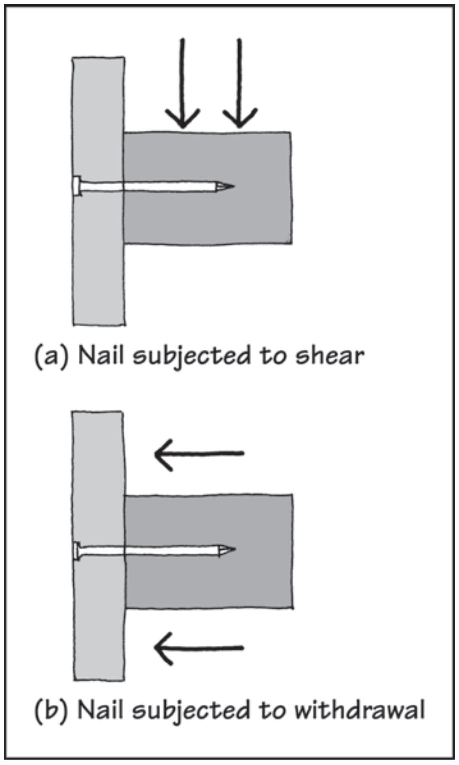


FIGURE 14.36 Nails subjected to **(a)** shear and **(b)** withdrawal.

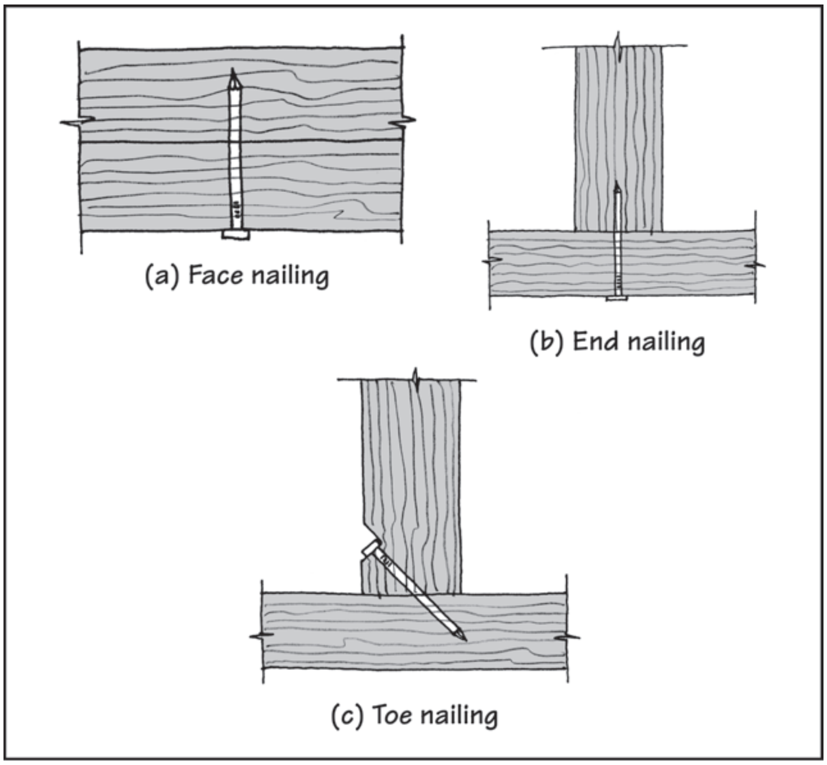


FIGURE 14.37 Types of nailed connections used in wood frame construction.

nails, trying to pull the connected members apart, Figure 14.36. Three types of nailed connections are used in wood frame construction, Figure 14.37:

- Face-nailed connection
- End-nailed connection
- Toe-nailed connection

A face-nailed connection is the strongest of the three because it has the highest withdrawal resistance. The withdrawal resistance of a nail is a function of the nail's orientation with respect to the grain of wood in the holding member (the member that contains the tip of the nail). If the axis of the nail is parallel to the grain of wood in the holding member, the withdrawal resistance is extremely small. In practice, it is assumed equal to zero. Withdrawal resistance is highest if the nail's axis is perpendicular to the grain of wood in the holding member, such as in a face-nailed connection.

End nailing, in which the nails are parallel to the grain in the holding member, is the weakest connection. End nailing is acceptable only in situations where the member is not subjected to withdrawal. Toe nailing is stronger than end nailing, but it is used where access for end nailing is unavailable. A fourth type of connection, referred to as *blind nailing*, is used in finished wood flooring.

POWER-DRIVEN NAILING AND STAPLING

Although manual hammering is still used to drive nails, power-driven nailing (through pneumatic or electric nailing guns) has become the preferred method of making connections, Figure 14.38. In the power-driven system, nailing is achieved by the pull of a trigger, which not only speeds the process substantially but is also less tiring for the worker.

Nails used in nailing guns are thinner and smaller than the corresponding pennyweight sizes of hand-driven nails. Manufacturers provide the equivalence between the nails used in guns and the nails used in manual hammering. Power stapling is also a recognized method of fastening wood members and is generally used as an alternative to 8d or 6d nails.

NAIL POPPING

Nail popping—nails sticking out of the wood members—is a problem primarily in floor sheathing that is nailed to the joists.

FIGURE 14.38 A typical nailing gun.

NOTE

The Importance of the Lowly Nail

Though seemingly insignificant, nails are an extremely important component in contemporary wood construction. It is the nails that hold the thousands of individual wood members together. It is estimated that approximately 35 nails are used in 1 square foot of a typical wood frame dwelling. Thus, in an average modern U.S. home (of about 2,500 ft^2), approximately 90,000 nails may be used. Before the introduction of nail guns, driving such a large quantity of nails was not only time consuming but also labor intensive. The use of nail guns has dramatically increased construction efficiency by increasing the speed and reducing the cost of making connections.

With such a large quantity of nails required, it is obvious that without the discovery of the mass production of nails, which made nails affordable and available in large quantities, contemporary wood construction would not have been possible [Ref. 14.1]. Until the dawn of the nineteenth century, nails were generally hand made by forging a piece of iron. They were, therefore, expensive and had limited availability. A legend has it that nails were so important and expensive at that time that old, dilapidated homes were burned to retrieve them. After sifting nails from the ashes, a blacksmith would straighten them for reuse.

Because they were hand made, nail making was a cottage industry, and many people, including some well-to-do ones, made nails for personal use and (or) sale using their fireplaces. The third U.S. President (1801–1809), Thomas Jefferson, had a nail-making shop at his Monticello farm [Ref. 14.2].

Nail-making machines at the time made nails by shearing them from steel plates. Sheared nails, referred to as *cut nails*, were tapered at the tip on one face; the other face had a constant thickness, representing the thickness of the plate from which they were sheared. The tips of hand-forged nails, by contrast, were tapered all around.

The making of cut nails, though much faster than hand forging, was still quite labor intensive compared with modern nail making because different machines were used for shearing, heading, and tipping. The introduction of improved nail-making machines around 1850, which cut and headed the nails using a single machine, increased their availability and affordability. Since then, nail-making technique has advanced considerably. Today, most nails are made from wires, though cut nails are still made because of their greater holding power compared with that of round wire nails.

It occurs as the floor joists dry and shrink in size, which pulls them away from the sheathing, Figure 14.39. Because the load on sheathing is downward, the nails pop out through the sheathing.

Nail popping is particularly critical if the floor finish consists of thin, easily penetrable material, such as vinyl tiles. It can be reduced by using I-joists, trussed joists, or solid lumber joists that are relatively drier. Field gluing the sheathing to the joists before nailing them further reduces nail popping, Figure 14.40. Gluing also stiffens the floor by integrating the sheathing with the floor joists to form a floor consisting of T-sections, in which the sheathing works as the flange of the T-section and the joist works as the web.

SCREWS AND BOLTS

Although screws have a much higher withdrawal resistance (holding power) than nails, they are not often used in structural wood framing because they take longer to install and are more expensive than nails. However, they are commonly used in cabinet work, in furniture, and for fastening door and window hardware such as hinges. Drywall screws, used for attaching wallboard, are also commonly used. In heavy structural members, lag screws or bolts are used. A lag screw has the shank of a screw but the head of a bolt, Figure 14.41.

14.10 SHEET METAL CONNECTORS

A number of metal connectors are used in contemporary wood buildings. Nails used in conjunction with metal connectors are loaded in shear rather than in complete or partial withdrawal. Standard connectors are made of galvanized steel, but stainless steel connectors are also available. Metal connectors can be divided into two types:

- Light-gauge sheet steel connectors (generally 16 to 20 gauge) are used in conventional wood framing, such as the joints between a beam and floor joists, between rafters or trusses and the top plate, between studs and the bottom plate, and so on.
- Heavy-gauge sheet steel connectors (generally 7 to 12 gauge) are used in heavy wood framing, such as in joints between a post and a beam, between two beams, between a post and the foundation, and so on. They are also used in high-wind or high-seismic regions in wood light-frame buildings, which would otherwise require light-gauge connectors.

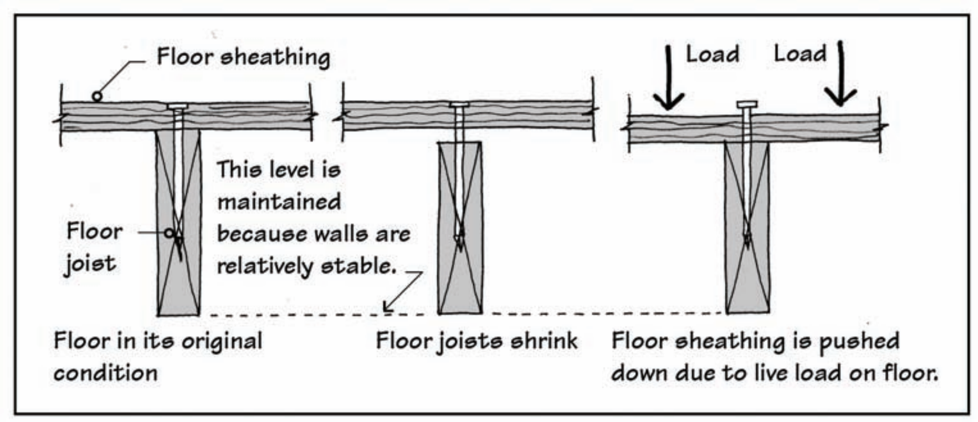

Floor sheathing
Load
Load
This level is maintained because walls are relatively stable.
Floor joist
Floor in its original condition
Floor joists shrink
Floor sheathing is pushed down due to live load on floor.

FIGURE 14.39 Mechanics of nail popping.

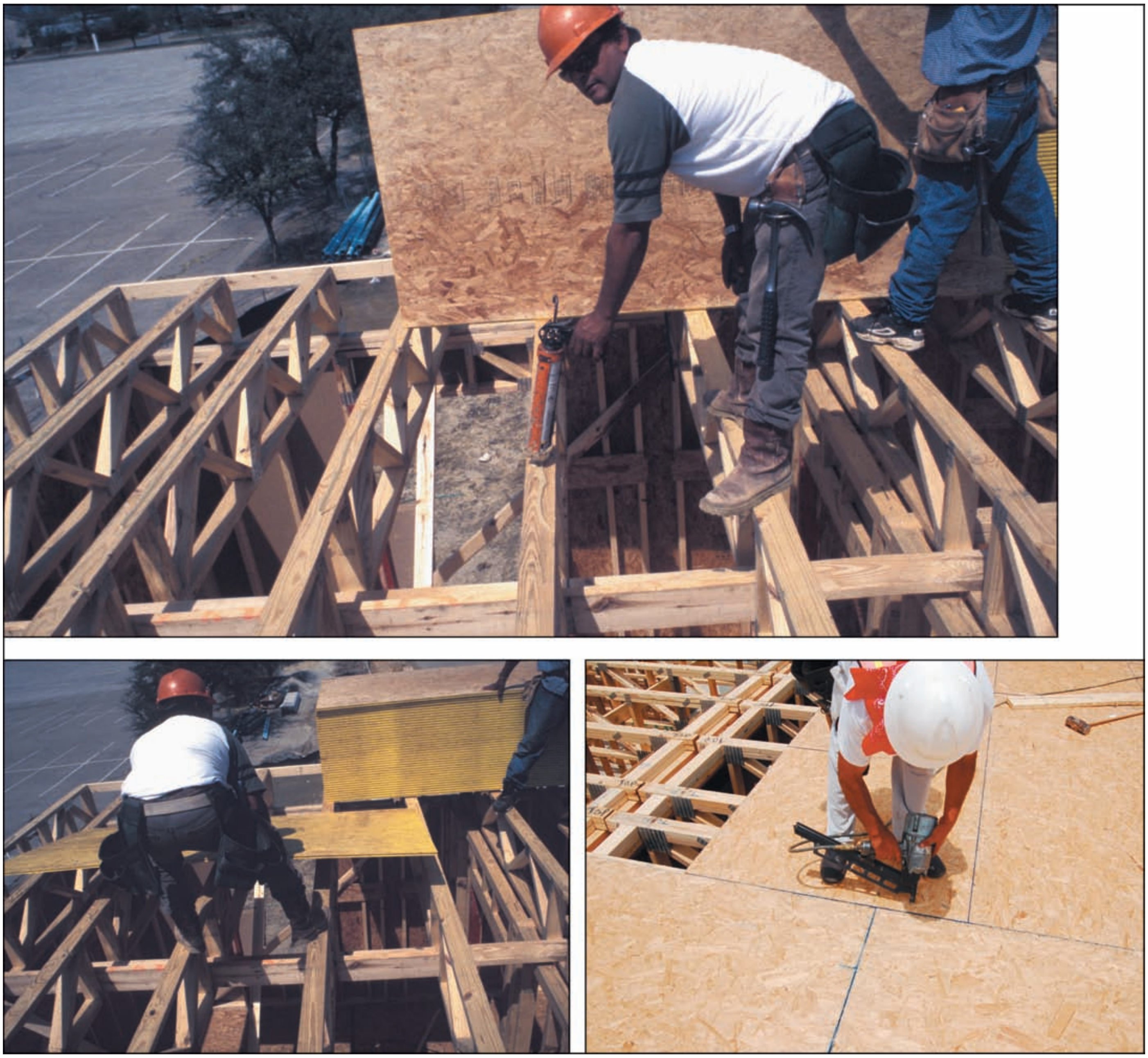


FIGURE 14.40 Gluing and nailing of floor sheathing to floor joists.

Steel connectors are integral to wood framing, but only a few commonly used connectors are discussed here. The most commonly used connector is a joist hanger, which is used for connecting floor joists with a supporting beam. Joist hangers can reduce the overall height of the floor because, without their use, the joists will have to rest over the beam, Figure 14.42.

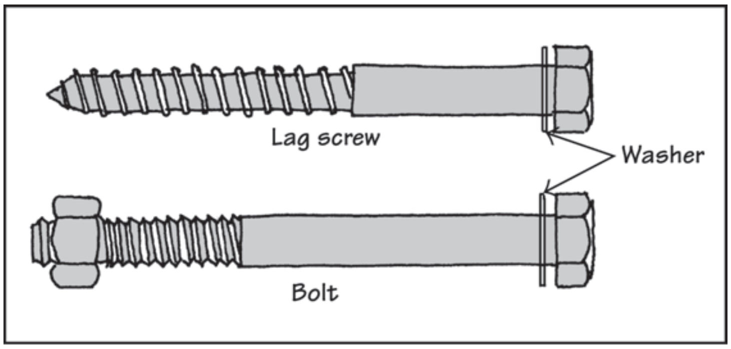


FIGURE 14.41 Lag screws and bolts used in heavy wood framing.

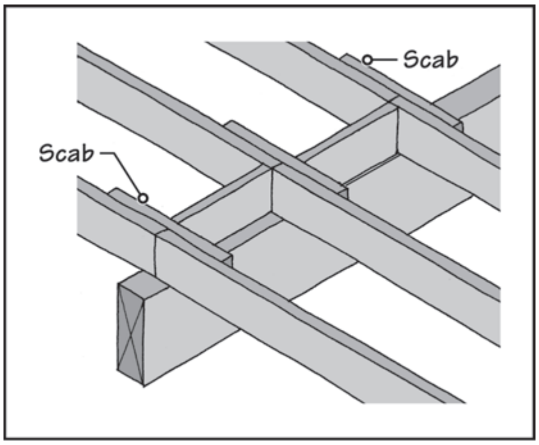


FIGURE 14.42 Floor joists resting over a supporting beam. See also Figure 15.24.

FOCUS ON SUSTAINABILITY

Sustainability in Engineered Wood Products

Like lumber, manufactured wood products are among the most sustainable of building materials, especially when produced from wood sources certified by the Forest stewardship council (Fsc).

Many of the characteristics that make manufactured wood products highly desirable as construction materials also make them more sustainable products. For instance, I-joists are structurally efficient and can be ordered to size and length, reducing job-site waste. They use only 50% as much wood as comparable sawn lumber members and can be manufactured using fast-growing second- or third-growth trees, mixed species, or other underutilized species. The same applies to other engineered wood products.

One of the long-standing debates related to manufactured wood products is that they are produced with formaldehyde resin adhesives. These adhesives emit a gas into the air that is known to cause adverse health effects in humans. Emission levels are highest when the product is new, but they decrease over time. In the United States, the Department of Housing and Urban Development has set standards for allowable levels of formaldehyde emissions, which manufacturers currently meet. With increasing emphasis on indoor air quality in sustainable construction, it is expected that standards will become more stringent in the future.

Two types of formaldehyde are commonly used. Urea formaldehyde is generally used for products designed for indoor applications. These include particle board, used as a floor underlayment and in shelving; hardwood plywood paneling; and medium-density fiberboard, used in cabinets and furniture. Some of the hazardous effects can be mitigated by encasing these products in laminates. The use of adequate ventilation and the maintenance of moderate interior humidity levels also help reduce potential problems.

Phenol formaldehyde resin emits formaldehyde gas at much lower levels. It is darker in color and is used to manufacture products such as softwood plywood and oriented strandboard intended for exterior use. Designers are beginning to specify the use of these materials for interior applications as a way to reduce problems with indoor air quality.

Two types of joist hangers are commonly used: (a) face-mounted hanger and (b) top-mounted hanger, Figure 14.43. Face-mounted hangers are used to connect joists to a beam or header. Top-mounted hangers are used where face mounting is not possible, such as when connecting joists to a steel beam, Figure 14.44.

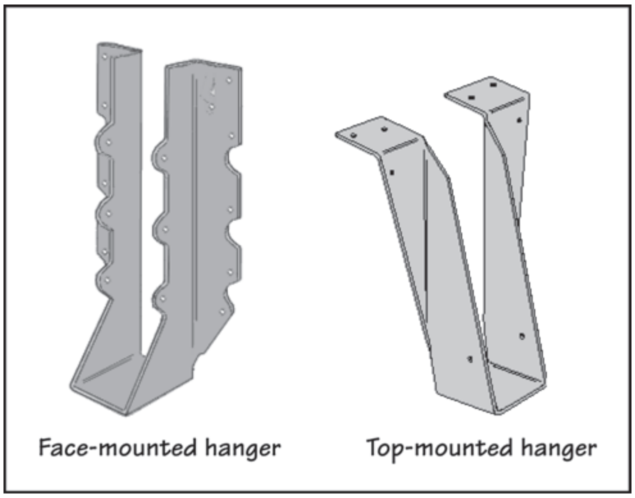


FIGURE 14.43 Typical joist hangers.

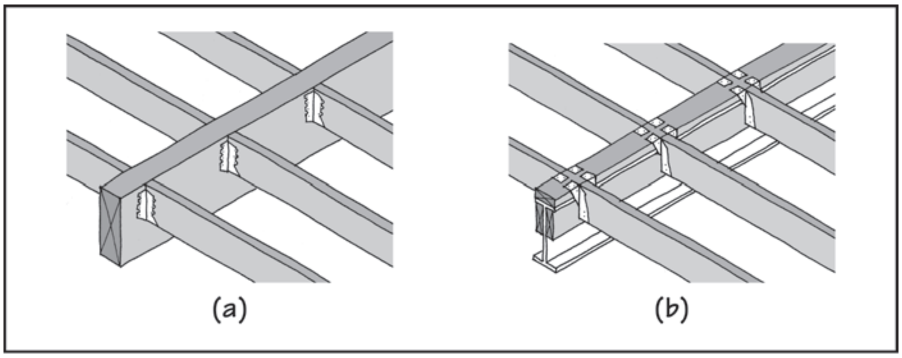


FIGURE 14.44 **(a)** The use of face-mounted joist hangers. **(b)** The use of top-mounted joist hangers.

Each question has only one correct answer. Select the choice that best answers each question.

20. Several different types of nails are used in wood frame construction. They are typically distinguished from each other by the
- **a.** nail head and nail shank.
- **b.** nail head and nail tip.
- **c.** nail tip and nail shank.
- **d.** nail head and type of threads.
- **e.** none of the above.

21. The nails most commonly used in wood frame construction are
- **a.** 4d, 6d, 9d, and 12d.
- **b.** 6d, 12d, 18d, and 24d.
- **c.** 6d, 10d, 16d, and 20d.
- **d.** 6d, 8d, 10d, and 16d.
- **e.** 6d, 8d, 10d, and 12d.

22. Nails work best when they are subjected to
- **a.** shear.
- **b.** tension.

23. Which of the following nailed connections is the strongest?
- **a.** Face nailing
- **b.** Toe nailing
- **c.** End nailing

24. Nail popping is primarily a problem in floor sheathing and is caused by the shrinkage of floor sheathing.
- **a.** True
- **b.** False

25. Joist hangers are steel connectors
- **a.** that connect floor joists with a supporting beam.
- **b.** that connect floor joists with the supporting wall.
- **c.** that connect floor joists with floor sheathing.
- **d.** all of the above.

26. The adhesives used in making engineered wood products contain
- **a.** urethane.
- **b.** styrene.
- **c.** formaldehyde.
- **d.** lignin.
- **e.** none of the above.

27. Gaseous emissions produced by engineered wood products decrease over time.
- **a.** True
- **b.** False

REVIEW QUESTIONS

1. Using sketches and notes, explain the difference between a balanced and an unbalanced glulam beam and the situations in which they are specified.
2. Using sketches and notes, explain the composition of a wood I-joist. What are the advantages and disadvantages of wood I-joists compared with solid lumber?
3. Using a sketch and notes, explain the following terms related to a wood roof truss: (a) *top chord*, (b) *bottom chord*, (c) *web member*, (d) *panel point*, and (e) *nail plate*.
4. Using a sketch, explain the difference between a roof truss and a floor truss. In which situations will you consider the use of wood floor trusses?
5. Which type of nail is commonly used for connections between framing members in wood light-frame structures? How do we specify the size of nails?
6. Discuss the relative advantages and disadvantages of OSB and plywood panels.
7. With the help of an example, explain what type of information is provided in the grade stamp of a typical performance-rated engineered wood panel.
8. Using sketches, illustrate the following connections in wood frame members: (a) face-nailed connection, (b) end-nailed connection, and (c) toe-nailed connection.
9. With the help of a three-dimensional sketch, explain the connection of a floor joist with a supporting beam using a joist hanger.

CHAPTER 15

Wood Light-Frame Construction–I

CHAPTER OUTLINE

15.1 Evolution of Wood Light-Frame Construction

15.2 Contemporary Wood Light-Frame—The Platform Frame

15.3 Frame Configuration and Spacing of Members

15.4 Essentials of Wall Framing

15.5 Framing Around Wall Openings

15.6 Essentials of Floor Framing

15.7 Roof Types and Roof Slope

15.8 Essentials of Roof Framing

15.9 Vaulted Ceilings

15.10 Sheathing Applied to a Frame

15.11 Equalizing Cross-Grain Lumber Dimensions

15.12 Wood Light Frame and the International Building Code

15.13 Building Taller With Wood Light Frame

PRINCIPLES IN PRACTICE: Constructing a Two-Story Wood Light-Frame Building

PRINCIPLES IN PRACTICE: How a WLF Building Resists Loads

EXPAND YOUR KNOWLEDGE: Wood Construction Prior to Balloon Frame

Wood light-frame (WLF) construction is the dominant system for contemporary residential and light commercial construction in the United States and several other countries. It is examined in this chapter and the next. The framing aspects of WLF construction are considered in this chapter, and the interior and exterior finishes in the next chapter.

This chapter begins with a brief overview of the evolution of WLF, followed by a discussion of the organizational principles of this construction system. Then the essential characteristics and components of the system, including the floor, wall, and roof framing and sheathing, are investigated. At the end of this chapter, two Principles in Practice features are presented. The first provides an example of the WLF construction process and sequence, and the second describes how loads are resisted by a typical WLF structure.

Concluding this chapter is an Expand Your Knowledge section that provides a brief account of the wood construction that existed in the United States before the discovery of (and its evolution into) the contemporary WLF construction.

15.1 EVOLUTION OF WOOD LIGHT-FRAME CONSTRUCTION

As the European settlers colonized America and built on the new land, they tried to re-create the ambience and spirit of their original countries. Early American buildings and construction systems were, therefore, derived mainly from European practices. Wood light-frame construction, on the other hand, was invented in the United States and is uniquely American.

WLF construction was first used around 1830 in the Chicago area, which was then developing as a major urban center in the United States. There is some controversy about who should be credited with the development of this new system. Two persons—Augustine Taylor and George Washington Snow—both carpenters from the Chicago area, are said to have invented the system independent of each other.

The WLF system has evolved over nearly two centuries and has adapted marvelously to several technical innovations in buildings, such as insulation, electricity, piped water supply, and sewage disposal, which did not exist during the time of Taylor or Snow. The system's adaptability and the ease with which it could be used led to its success and popularity. So successful has the system been that it is now the dominant system for contemporary residential and light commercial construction in the United States and several other countries.

BALLOON FRAME

Prior to the invention of the WLF system, most buildings in the United States were built of thick masonry walls, heavy timber posts, beams, and thick wood plank floors and roofs. The joints between heavy timber posts and beams consisted of mortise-and-tenon, or dovetail, joints (see the Expand Your Knowledge section at the end of this chapter). Because no nails or screws were used to secure the joints, expert craftsmanship was needed to provide tight joints.

When the WLF system was invented to replace the heavy construction system just described, it was called the *balloon frame*. It consisted of thin, closely spaced vertical wood members (called *studs*) and similar floor and roof framing members (called *joists* and *rafters*).

The connections between members were made with simple nails. Measuring, hammering, and sawing were, therefore, the only skills needed for the connections, making sophisticated carpentry and joinery skills unnecessary. In fact, the entire structural frame of a WLF building could be erected by a relatively unskilled crew of two or three people.

An additional advantage of the WLF system lay in its lightweight members, which needed little effort to hoist and install. Because the members were small in cross section, the total amount of wood consumed in a balloon frame building was only a fraction of that consumed in a traditionally built building of the same size. In fact, many historians believe that various U.S. cities could not have developed as rapidly as they did without the invention of the balloon frame.

As with most other inventions, the birth of the WLF system may be attributed to necessity. The necessity arose from an abundance of wood in the new country, where skilled carpenters were scarce. Immigrants at that time consisted largely of poor, unskilled workers unable to find work in Europe. This was in direct contrast to the wealth of skilled carpenters in Europe, where forests were gradually becoming depleted.

The term *balloon frame* was coined out of contempt by the critics of the system at the time, who considered it too insubstantial to withstand the forces of nature. Although time proved them wrong, the term continued to be used. In the balloon frame, the studs run the full height of the building, from the sill plate at the bottom to the top plate under the rafters. The intermediate floor joists (in a two-story building) rest on a 1 × 6 (or 1 × 4) ledger—called a *ribband*—notched into the studs, Figure 15.1.

In addition to ribbands, fire-stops are provided at floor lines in a balloon frame, Figures 15.1 and 15.2. Without the fire-stops, the air space between the studs is continuous from the top to the bottom. This creates a fire risk because a fire occurring in the stud cavity of one floor can spread to another floor. The fire-stops separate the cavities and deprive the fire of the oxygen required for its growth.

The continuity of studs was recognized as a major limitation of the balloon frame. This limitation became more acute as the greater use of wood reduced the availability of long, straight members and made them more expensive. The balloon frame was, therefore, modified over time into the *platform frame*, in which the individual studs are only one story high. Contemporary WLF construction consists mainly of the platform frame, the subject of discussion in this chapter.

NOTE

Balloon Frame and Nails

As stated, the balloon frame was invented in the United States in 1830. However, as with all innovations, wide acceptance of the balloon frame had to wait for the right environment to emerge. That happened with the mass production of nails in the mid-nineteenth century (see the margin note in Section 14.9 entitled "The Importance of the Lowly Nail").

The balloon frame was indeed much lighter and simpler to construct than the wood construction system that preceded it (see the Expand Your Knowledge section at the end of this chapter). However, the balloon frame construction was heavily dependent on nailed connections. Without the availability and affordability of nails, the balloon frame construction would not have gone much further [Ref. 15.1]. The convergence of the two innovations mass production of nails and invention of the balloon frame revolutionized wood construction. As nail manufacturing advanced, making nails inexpensive, balloon frame construction increased rapidly throughout the United States and other countries.

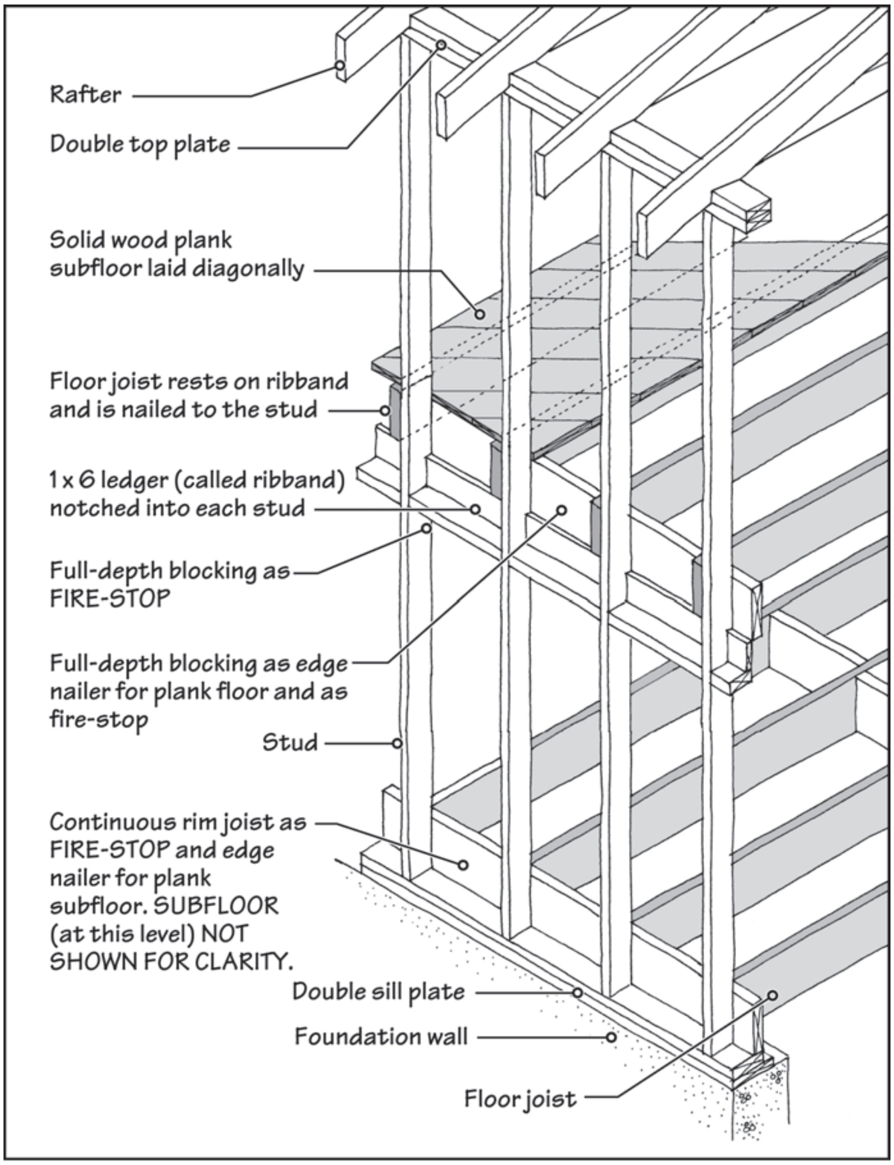

Rafter
Double top plate
Solid wood plank subfloor laid diagonally
Floor joist rests on ribband and is nailed to the stud
1 x 6 ledger (called ribband) notched into each stud
Full-depth blocking as FIRE-STOP
Full-depth blocking as edge nailer for plank floor and as fire-stop
Stud
Continuous rim joist as FIRE-STOP and edge nailer for plank subfloor. SUBFLOOR (at this level) NOT SHOWN FOR CLARITY.
Double sill plate
Foundation wall
Floor joist

FIGURE 15.1 A typical balloon frame construction—a precursor of the contemporary platform frame construction.

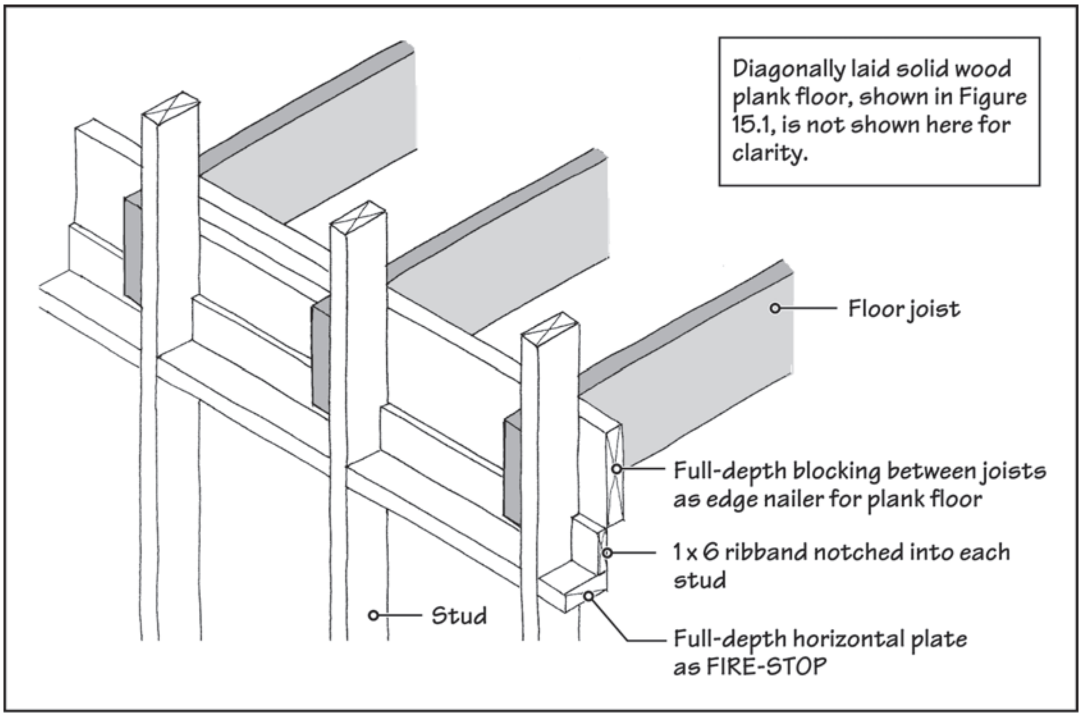

Diagonally laid solid wood plank floor, shown in Figure 15.1, is not shown here for clarity.
Floor joist
Full-depth blocking between joists as edge nailer for plank floor
1 x 6 ribband notched into each stud
Stud
Full-depth horizontal plate as FIRE-STOP

FIGURE 15.2 Detail of balloon frame construction at the intermediate floor level.

15.2 CONTEMPORARY WOOD LIGHT FRAME—THE PLATFORM FRAME

In the balloon frame, wall framing, floor framing, and roof framing are completed for the entire building before the structural floor (referred to as the *subfloor*, or *floor sheathing*) is constructed. In the platform frame, on the other hand, the subfloor at the first floor level is completed soon after laying of floor joists at that level. This subfloor provides a platform for the workers to stand on and build the following story.

With the subfloor completed, the first-floor walls are then erected. These walls bear on the subfloor. Later, the floor joists for the second floor are erected, which are then sheathed with plywood or oriented strandboard (OSB) panels to make the subfloor for the second story. If there is an additional story in the building, it is built exactly the same way as the lower story. Finally, the roof framing is completed. In other words, in the platform frame, the structural frame is erected story by story.

A three-dimensional view of a typical platform frame structure is shown in Figure 15.3. Because the walls are not continuous, fire-stops are automatically provided at each floor level. Thus, there is no need to add special members for fire-stopping, as is the case in a balloon frame. Note that the roof framing is identical in both the platform frame and the balloon frame.

The platform frame system not only facilitated construction, it also increased the safety of the workers because they could use the floor platform as the scaffold for constructing the subsequent floor. Exterior scaffolding and tall construction ladders were unnecessary. Additionally, it became possible to build structures with more than two stories. With the balloon frame, the practical height limitation of the building was two stories because studs longer than two stories were—and are—not easily available. (For details on the process and

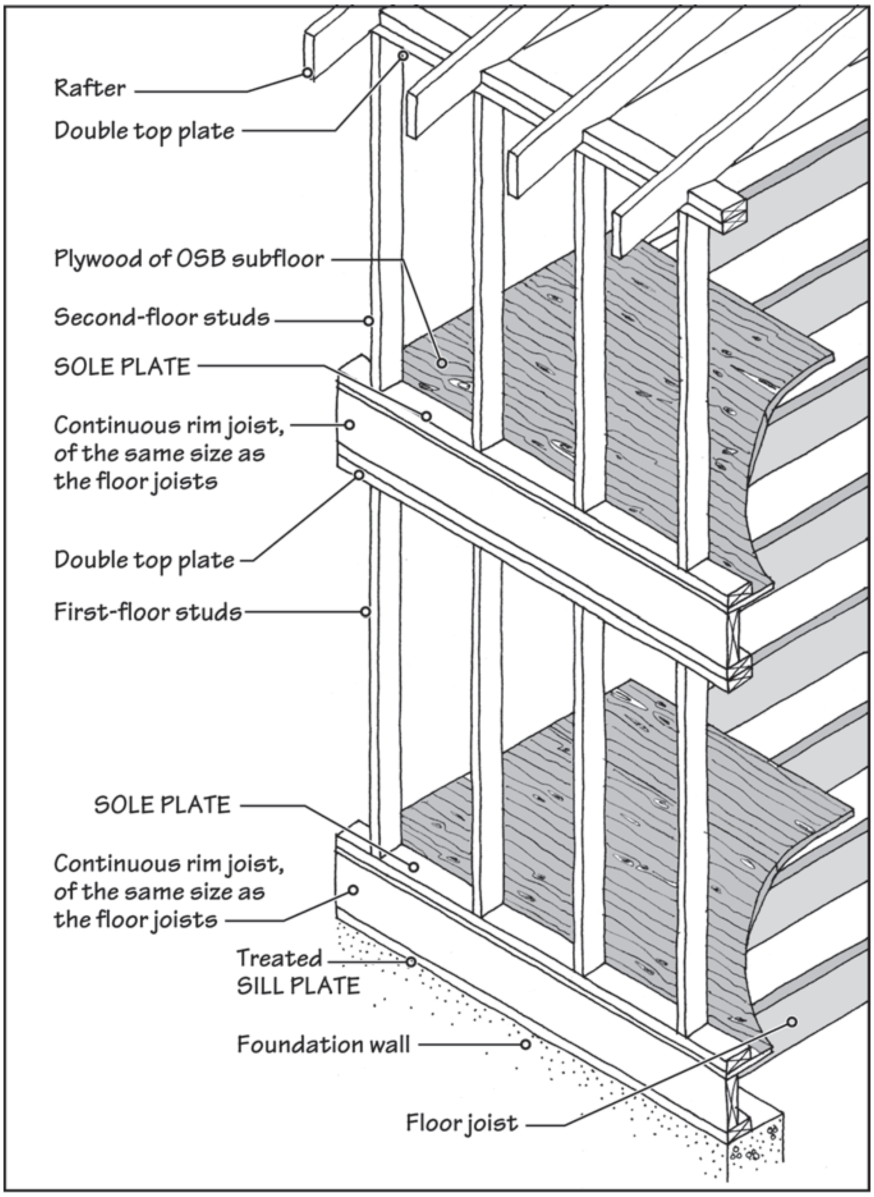

Rafter
Double top plate
Plywood of OSB subfloor
Second-floor studs
SOLE PLATE
Continuous rim joist, of the same size as the floor joists
Double top plate
First-floor studs
SOLE PLATE
Continuous rim joist, of the same size as the floor joists
Treated SILL PLATE
Foundation wall
Floor joist

FIGURE 15.3 A typical platform frame construction.

sequence of the construction of a typical WLF building, see the first Principles in Practice section at the end of this chapter.

DIMENSIONAL STABILITY OF BALLOON AND PLATFORM FRAMES

The continuity of studs in a balloon frame, however, gives it some benefits over the platform frame. For instance, the balloon frame is dimensionally more stable because it has a much smaller overall cross-grain lumber dimension than the platform frame.

Figure 15.4 shows the cross sections through a typical platform frame and a typical balloon frame. Assuming that 2 × 12 solid lumber floor joists are used in both frames, the total cross-grain lumber in the platform frame is 33 in., compared to 6 in. in a two-story balloon frame. Because lumber shrinks negligibly along the grain but significantly across the grain (Section 13.5), the shrinkage and swelling in a balloon frame are much smaller than in a platform frame.

Excessive shrinkage and swelling result in nail popping and cracking of brittle finishes applied to the frame, such as gypsum board and brick veneer. The detailing of the platform frame to accommodate shrinkage and swelling effects is covered in Section 15.11.

STRUCTURAL STABILITY OF BALLOON AND PLATFORM FRAMES

An additional advantage of the balloon frame is its greater structural stability. Continuous studs provide a more positive connection between the first and second floors of a balloon frame, giving greater strength and stability in resisting lateral loads.

In the platform frame, the connection between the two floors is provided by nailing the bottom plate of walls to the underlying floor frame. Additional connection is provided through the exterior sheathing. The connection so obtained between the floors is, however, not as strong as that provided by continuous studs. Therefore, in high-wind or seismic

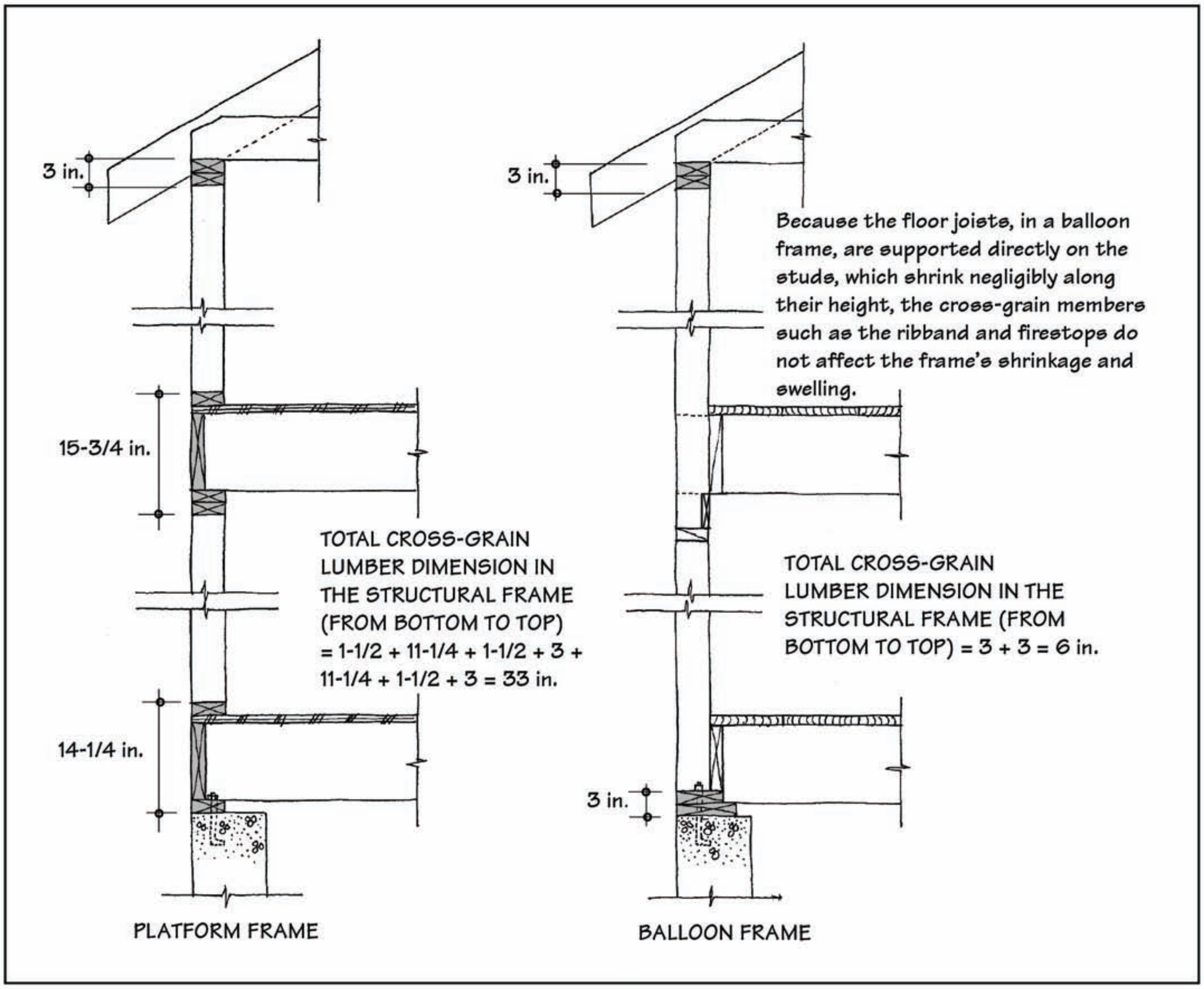

3 in.
15-3/4 in.
14-1/4 in.
TOTAL CROSS-GRAIN LUMBER DIMENSION IN THE STRUCTURAL FRAME (FROM BOTTOM TO TOP) = 1-1/2 + 11-1/4 + 1-1/2 + 3 + 11-1/4 + 1-1/2 + 3 = 33 in.
PLATFORM FRAME
3 in.
Because the floor joists, in a balloon frame, are supported directly on the studs, which shrink negligibly along their height, the cross-grain members such as the ribband and firestops do not affect the frame's shrinkage and swelling.
TOTAL CROSS-GRAIN LUMBER DIMENSION IN THE STRUCTURAL FRAME (FROM BOTTOM TO TOP) = 3 + 3 = 6 in.
3 in.
BALLOON FRAME

FIGURE 15.4 Cross sections through the structural frames of typical platform and balloon frames, highlighting the cross-grain lumber members in each.

regions, a platform frame requires metal straps and connectors to improve the connectivity between floors. See the second Principles in Practice section at the end of this chapter.

15.3 FRAME CONFIGURATION AND SPACING OF MEMBERS

A common feature of the three principal structural elements—the walls, floors, and roof—of a platform frame building is that each of these elements is made of several parallel, closely spaced, repetitive members joined at each end to a continuous cross member that runs perpendicular to the parallel members, Figure 15.5. Cross members connect the parallel members together to form a *frame* and also play an important structural role.

In a wall assembly, the cross members are the top and bottom plates. In a floor assembly, the cross member at each end is a continuous member of the same size as the joists, called the *rim joists* or *band joist*. In a rafter-and-ceiling-joist assembly, the top plates of the supporting walls on either side function as the cross members. The triangular rafter-and-ceiling joist assembly constitutes repetitive members. In a trussed roof, the trusses are the repetitive members.

Most framing members in a WLF building are 2-by members (the actual thickness is $1\frac{1}{2}$ in.). Generally, 2 × 4 or 2 × 6 members are used for walls; 2 × 8, 2 × 10, or 2 × 12 members are used for floor joists; and 2 × 6, 2 × 8, or 2 × 10 members are used for rafters.

The center-to-center spacing of members is either 12 in., 16 in., 19.2 in., or 24 in., as determined by the loads. These dimensions are also based on the size of the panels used as *sheathing* over the framing members—plywood, OSB, or gypsum board panels (typically 4 ft × 8 ft). Although 19.2-in. spacing is not commonly used, it is recognized as a possibility, because, like 12-in., 16-in., and 24-in. spacings, it also divides the 8-ft (96-in.) dimension by a whole number.

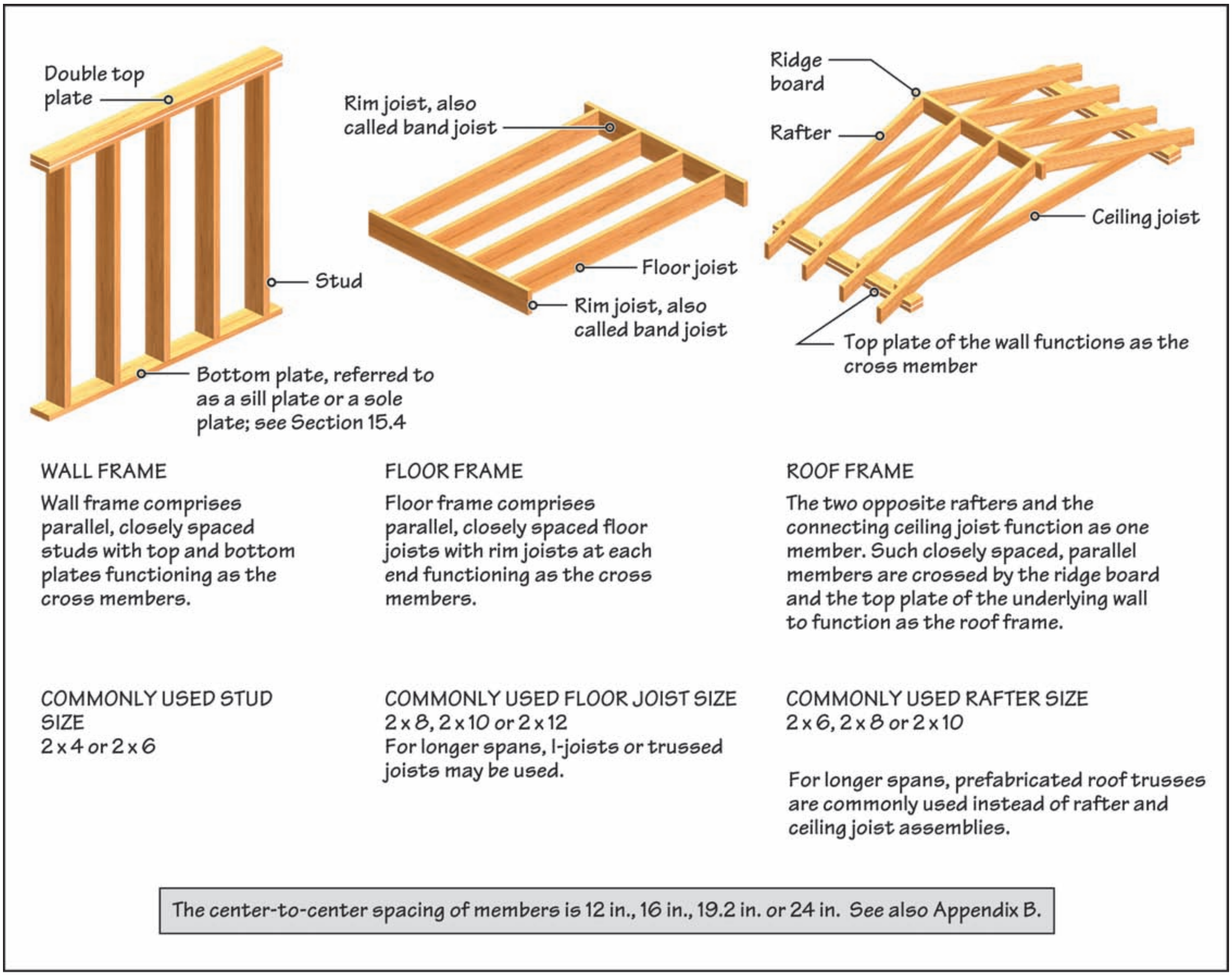

Double top plate
Stud
Bottom plate, referred to as a sill plate or a sole plate; see Section 15.4
Rim joist, also called band joist
Floor joist
Rim joist, also called band joist
Ridge board
Rafter
Ceiling joist
Top plate of the wall functions as the cross member
WALL FRAME
Wall frame comprises parallel, closely spaced studs with top and bottom plates functioning as the cross members.
FLOOR FRAME
Floor frame comprises parallel, closely spaced floor joists with rim joists at each end functioning as the cross members.
ROOF FRAME
The two opposite rafters and the connecting ceiling joist function as one member. Such closely spaced, parallel members are crossed by the ridge board and the top plate of the underlying wall to function as the roof frame.
COMMONLY USED STUD SIZE
2 x 4 or 2 x 6
COMMONLY USED FLOOR JOIST SIZE
2 x 8, 2 x 10 or 2 x 12
For longer spans, I-joists or trussed joists may be used.
COMMONLY USED RAFTER SIZE
2 x 6, 2 x 8 or 2 x 10
For longer spans, prefabricated roof trusses are commonly used instead of rafter and ceiling joist assemblies.
The center-to-center spacing of members is 12 in., 16 in., 19.2 in. or 24 in. See also Appendix B.

FIGURE 15.5 Each element of a WLF building (a wall, floor, or roof) is a frame consisting of several closely spaced, repetitive members that are connected at each end by a cross member.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. Roughly how old is WLF construction?
   - **a.** 1,000 years
   - **b.** 800 years
   - **c.** 600 years
   - **d.** 400 years
   - **e.** 200 years
2. When WLF was first discovered, it was called a
   - **a.** balloon frame.
   - **b.** rigid frame.
   - **c.** skeleton frame.
   - **d.** platform frame.
   - **e.** portal frame.
3. WLF construction originated in
   - **a.** the United Kingdom.
   - **b.** France.
   - **c.** Australia.
   - **d.** Norway.
   - **e.** the United States.
4. In the early version of WLF construction, the studs were continuous from the foundation to the roof.
   - **a.** True
   - **b.** False
5. In time, the early version of WLF construction was modified to what is now called a
   - **a.** balloon frame.
   - **b.** rigid frame.
   - **c.** skeleton frame.
   - **d.** platform frame.
   - **e.** portal frame.
6. The type of WLF construction that has the largest amount of cross-grain lumber is a
   - **a.** balloon frame.
   - **b.** rigid frame.
   - **c.** skeleton frame.
   - **d.** platform frame.
   - **e.** portal frame.
7. The framing members in a WLF building are generally
   - **a.** 1-by solid lumber members.
   - **b.** 2-by solid lumber members.
   - **c.** 3-by solid lumber members.
   - **d.** 4-by solid lumber members.
   - **e.** none of the above.
8. The center-to-center spacings of framing members in a WLF building are generally
   - **a.** 12 in., 16 in., or 24 in.
   - **b.** 12 in., 24 in., or 36 in.
   - **c.** 2 ft, 3 ft, or 4 ft.
   - **d.** 4 ft, 6 ft, or 8 ft.
   - **e.** virtually any spacing may be used, depending on the architectural and structural considerations.
9. The center-to-center spacing of framing members in a WLF building is mainly based on
   - **a.** age-old practice.
   - **b.** structural considerations.
   - **c.** the size of sheathing panels.
   - **d.** insulation requirements.
   - **e.** (b) and (c).

15.4 ESSENTIALS OF WALL FRAMING

The top plate in a wall assembly consists of two members, each of the same size as the studs. That is why it is referred to as a *double top plate*. Doubling the top plate makes it stronger and allows the floor joists or rafters to be placed anywhere on the top plate, Figure 15.6(a). The gravity loads from the joists or rafters are transferred to the double top plate, which functions as a beam supported on the studs. If a single top plate is used, the floor joists and rafters must align with the underlying studs, Figure 15.6(b). In this case, the loads from the joists or rafters would go directly into the studs, and the top plate does not have a beam action.

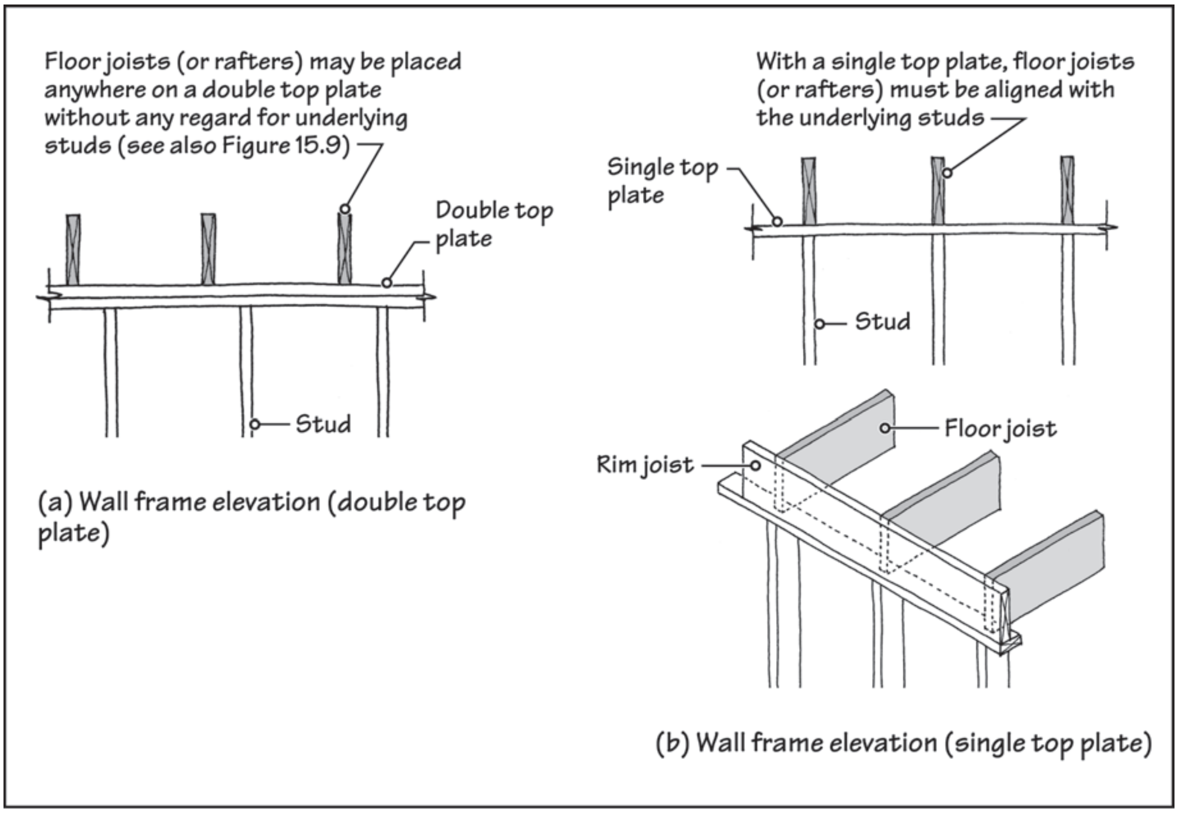
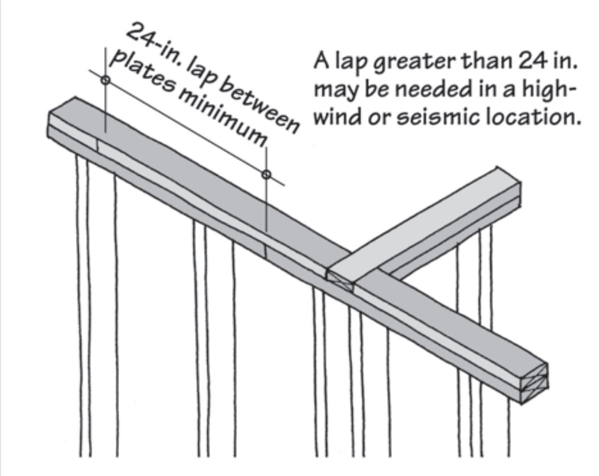

Floor joists (or rafters) may be placed anywhere on a double top plate without any regard for underlying studs (see also Figure 15.9)
Double top plate
Stud
(a) Wall frame elevation (double top plate)
With a single top plate, floor joists (or rafters) must be aligned with the underlying studs
Single top plate
Stud
Floor joist
Rim joist
(b) Wall frame elevation (single top plate)

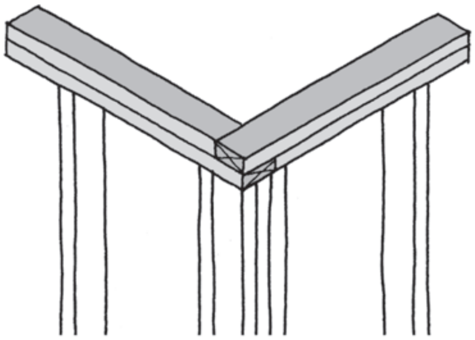
FIGURE 15.6 If a double top plate is used in a wall frame, the floor joists or roof rafters need not align with the underlying studs; see Figure 15.9 for exceptions.

Another reason for doubling the top plate is to provide structural continuity in the top plate. Structural continuity in the top plate is needed because the floor (and roof) works as a diaphragm in a wood frame building (see the second Principles in Practice section at the end of this chapter). This produces tension as well as compression in the top plate (of the exterior walls) under wind and earthquake loads.

Because a single top plate will have discontinuity at the joints, it will not be able to counteract tension. A double top plate can do so, provided that the joints between the two plates are staggered. Building codes mandate a minimum 24-in. lap at the joints between the two top plates. For the same reason, the two top plates must be staggered at the corners and junctions of the walls, Figure 15.7.


24-in. lap between plates minimum
A lap greater than 24 in. may be needed in a high-wind or seismic location.

(a) T-junction between walls



(b) Wall corner

FIGURE 15.7 The joints in the two top plates in a wall must be staggered as shown. Staggered joints are also required at wall T-junctions and corners.

Triple Top Plate

If the joists or rafters are 24 in. apart, each joist or rafter delivers a greater load on the wall than if they are spaced 16 in. apart or less. Therefore, building codes require that if the supporting wall is made of 2 × 4 studs spaced 24 in. on centers, and if the spacing between joists and rafters is more than 16 in. (19.2 in. or 24 in.), each joist or rafter should be located within 5 in. of the underlying studs, Figure 15.8. If this cannot be done, a third top plate is needed.

If the supporting wall is framed with 2 × 6 studs at 24 in. on centers (instead of 2 × 4 studs), the 5-in. restriction or the tripling of the top plate is not required. Because of its inconvenience, a triple top plate is seldom used.

Bottom Plate in a Wall Assembly

The bottom plate in a wall is typically a single plate, either a sill plate or a sole plate, depending on its location in the building. A *sole plate* is a plate that is not in contact with the foundation. Thus, the bottom plate of a second-floor wall is called the sole plate because it is connected to the wood subfloor, not to the foundation (Figure 15.3).

The bottom plate that is connected to the foundations is referred to as the *sill plate*. (Building foundations are discussed in detail in Sections 12.2 and 12.3.) At this stage, it is sufficient to know that the foundations for a WLF building may consist of any one of the following three types:

- A concrete slab-on-grade.
- Reinforced concrete (or concrete masonry) foundation walls. (With such a foundation, the ground floor consists of a wood frame floor with an underlying crawl space.)
- Reinforced concrete basement walls. (The ground floor in this case is also a wood frame floor with a basement space below.)

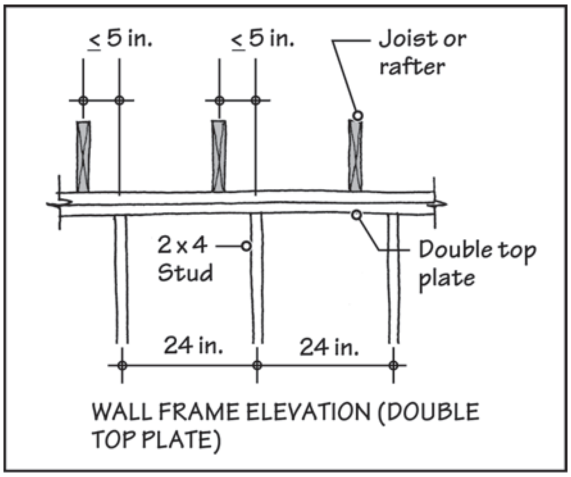


FIGURE 15.8 Restrictions on the placement of joists or rafters on a double top plate if 2 × 4 studs are at 24 in. on centers.

The sill plate is also referred to in some literature as the *mud sill*. It must be either a preservative-treated wood or a naturally decay-resistant wood species. The sill plate must be anchored to the foundations with bolts. This anchorage is critical because the entire building is secured to the foundations through these bolts.

Building codes require a minimum of $\frac{1}{2}$-in.-diameter steel bolts that must be embedded at least 7 in. into foundation concrete or masonry. The maximum spacing between bolts is 6 ft in low-wind and nonseismic locations, Figure 15.9(a). In high-wind and seismic locations, the anchor bolts are required to be larger and located closer together. Each sill plate length must have at least two bolts. Additionally, a bolt is required within 12 in. of the end of a sill plate length, Figure 15.9(b).

NOTE

Bottom Plate—Either a Sill Plate or Sole Plate

A *sill plate* is the bottom plate of a wall frame that is in direct contact with the foundation. It is generally made of preservative-treated wood, although codes allow a naturally decay-resistant wood species to be used instead of preservative-treated wood.

A *sole plate* is similar to a sill plate (the bottom horizontal member of a wall frame) that is not in direct contact with the foundation. A sole plate is made of an untreated lumber.

Bottom plate

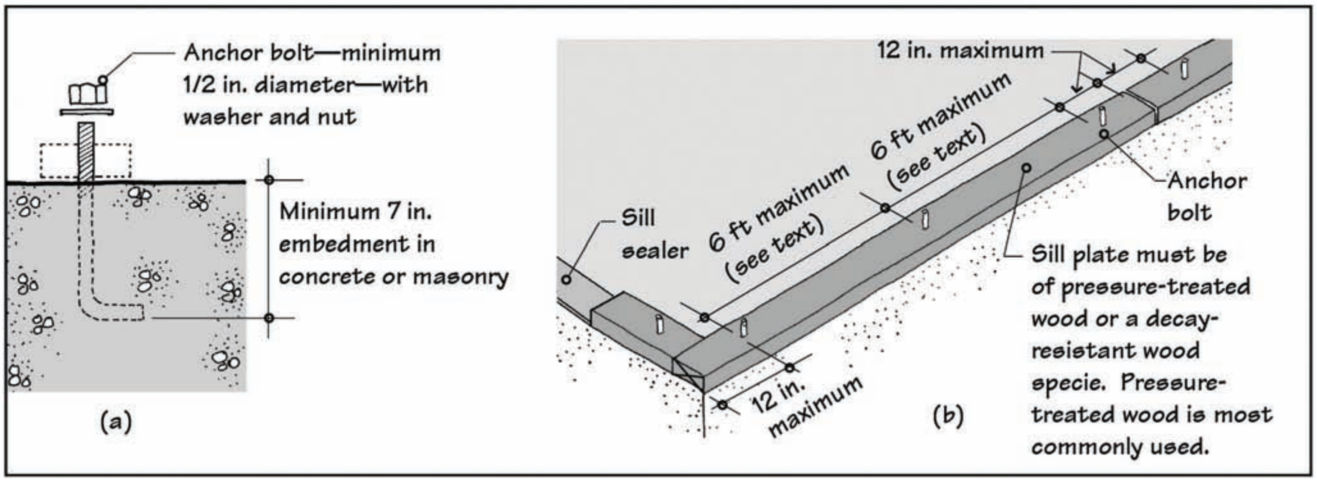
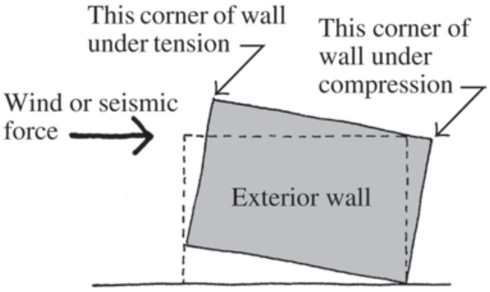

Anchor bolt—minimum 1/2 in. diameter—with washer and nut
Minimum 7 in. embedment in concrete or masonry
(a)
12 in. maximum
6 ft maximum (see text)
6 ft maximum (see text)
Sill sealer
Anchor bolt
Sill plate must be of pressure-treated wood or a decay-resistant wood specie. Pressure-treated wood is most commonly used.
12 in. maximum
(b)

FIGURE 15.9 Specifications and spacing of anchor bolts in a sill plate.

To reduce air infiltration, a compressible fibrous felt may be placed between the sill and the foundation, Figure 15.10. This helps to seal the gaps between the sill plate and the uneven surface of the foundation. In termite-infested areas, the use of a continuous termite shield (Section 13.14) is a good practice, in addition to using a preservative-treated sill plate.

NUMBER OF STUDS AT A WALL CORNER OR A T-JUNCTION BETWEEN WALLS

An exterior wall must function as a shear wall (see the second Principles in Practice section at the end of this chapter.) A shear wall is subjected to tension at one end and compression at the other end, caused by the tendency of the wall to overturn under the action of wind or earthquake loads. The compression caused by the lateral loads adds to the compression due to the gravity loads. Therefore, the corner of an exterior wall must be stronger than the field of the wall, requiring a minimum of three studs at the corner.


This corner of wall under tension
This corner of wall under compression
Wind or seismic force
Exterior wall

In addition to the structural consideration, the provision of three studs at a corner is required to obtain an adequate nailing surface for interior gypsum board and exterior sheathing. Two alternative details are typically used for a three-stud corner, Figure 15.11. This figure also shows a typical detail of studs at a wall T-junction, which also requires three studs.

15.5 FRAMING AROUND WALL OPENINGS

A typical framing around openings in a wall (doors or windows) is shown in Figure 15.12. A wall opening requires the use of *jack studs* on both sides of the opening. A jack stud is a partial-height stud that supports the lintel beam, generally referred to as a *header* (or *lintel header* in some literature). One jack stud on both sides of the opening gives $1\frac{1}{2}$-in. bearing for the header. This is adequate for a small opening in a one- or two-story building. If the opening size is large or if the number of floors in the building exceeds two, two or three jack studs may be needed.

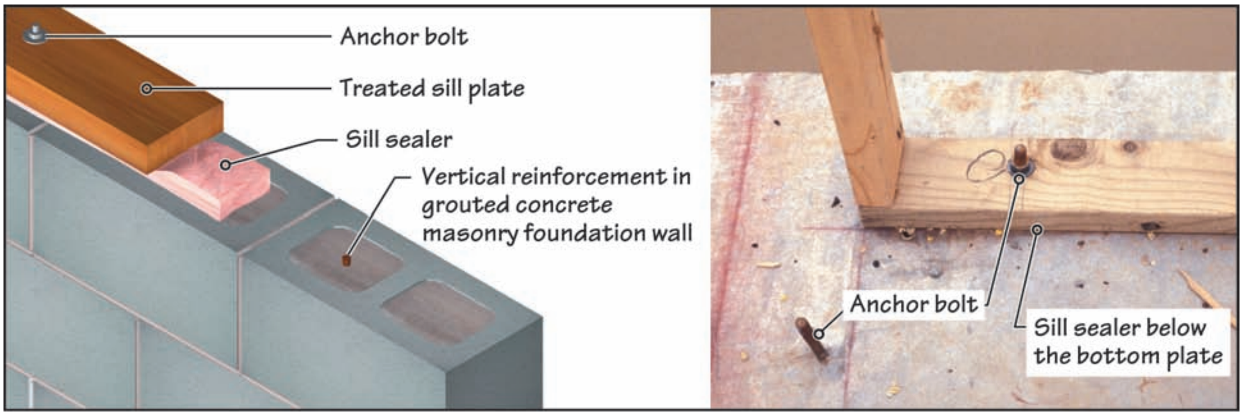

Anchor bolt
Treated sill plate
Sill sealer
Vertical reinforcement in grouted concrete masonry foundation wall
Anchor bolt
Sill sealer below the bottom plate

FIGURE 15.10 Sill sealer under a sill plate.

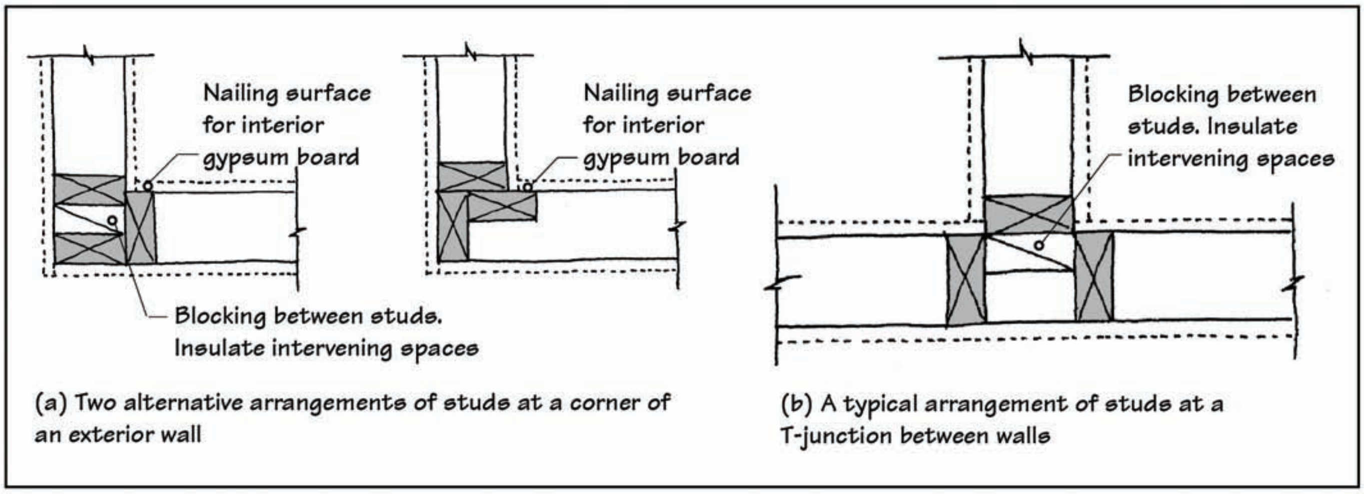
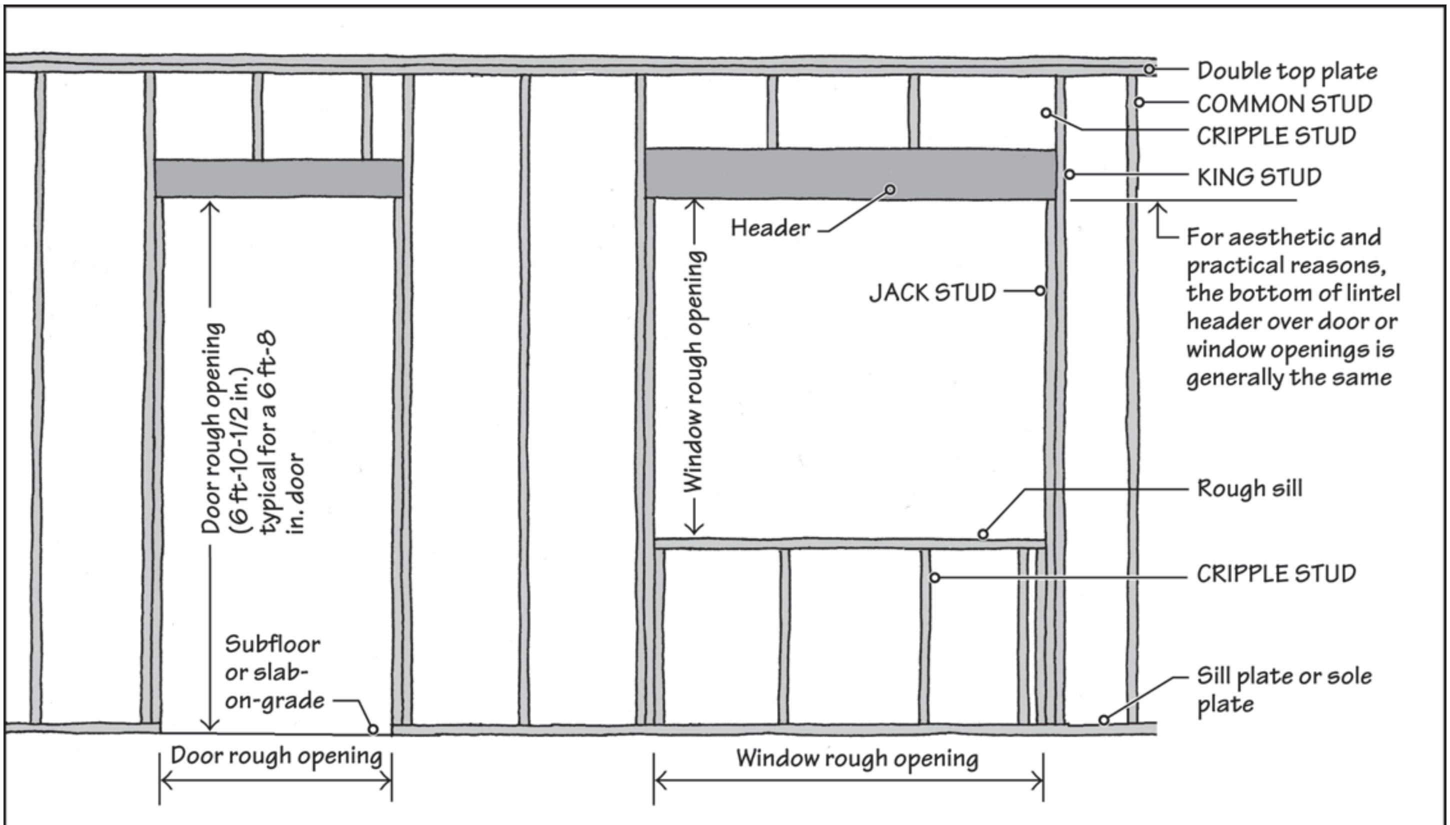

Nailing surface for interior gypsum board
Nailing surface for interior gypsum board
Blocking between studs. Insulate intervening spaces
Blocking between studs. Insulate intervening spaces
(a) Two alternative arrangements of studs at a corner of an exterior wall
(b) A typical arrangement of studs at a T-junction between walls

FIGURE 15.11 Typical arrangements of studs (shown in plan) at a corner of an exterior wall and a T-junction between walls.


Double top plate
COMMON STUD
CRIPPLE STUD
KING STUD
Header
JACK STUD
For aesthetic and practical reasons, the bottom of lintel header over door or window openings is generally the same
Door rough opening (6 ft-10-1/2 in.) typical for a 6 ft-8 in. door
Window rough opening
Rough sill
CRIPPLE STUD
Subfloor or slab-on-grade
Sill plate or sole plate
Door rough opening
Window rough opening

Number of Jack Studs and King Studs in Load-bearing Wall Openings

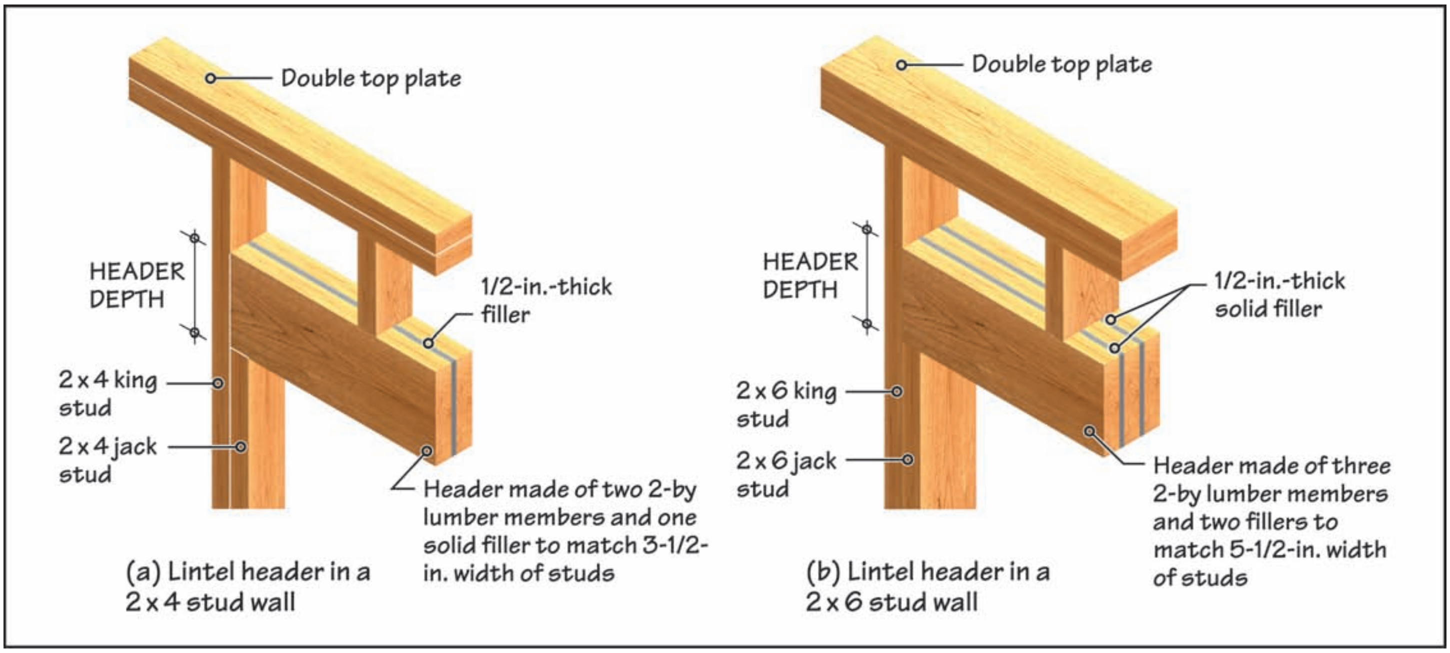
Although one jack stud has been indicated in this figure, two or three jack studs may be required if the opening is subjected to a greater dead load, which is a function of the number of floors above the opening and the roof snow load. Generally, for a load-bearing wall, the total number of jack studs on both sides of the opening should at least be equal to the number of common studs removed from the wall by the opening.

Similarly, although one king stud has been shown, in high-wind regions the use of two or three kings studs may be needed in a wall.

FIGURE 15.12 Wall framing around openings.

HEADER

A header is typically made of two or three 2-by lumber members, depending on the thickness of the wall. The members are face nailed to form a beam. If the wall is framed of 2 × 4 members, two 2-by lumber members are required, with a $\frac{1}{2}$-in.-thick filler, Figure 15.13. The filler is usually a plywood or an OSB sheet. For exterior walls, a rigid plastic foam insulation is used. In a 2 × 6 wall, three 2-by lumber members are required, with two filler sheets. For large openings, trussed headers (Figure 14.20) or glulam headers are used.


Double top plate
HEADER DEPTH
1/2-in.-thick filler
2 x 4 king stud
2 x 4 jack stud
Header made of two 2-by lumber members and one solid filler to match 3-1/2-in. width of studs
Double top plate
HEADER DEPTH
1/2-in.-thick solid filler
2 x 6 king stud
2 x 6 jack stud
Header made of three 2-by lumber members and two fillers to match 5-1/2-in. width of studs

(a) Lintel header in a 2 x 4 stud wall

(b) Lintel header in a 2 x 6 stud wall

FIGURE 15.13 Anatomy of a header made with 2-by lumber members.

PRECUT LENGTH OF STUDS AND OVERSIZED HEADERS

Lumber is usually available in lengths of 8 ft, 10 ft, 12 ft, and so on, up to a maximum length of 26 ft. (Some lumber dealers may stock lumber only up to a length of 22 ft.) A special precut length that is commonly used for studs is 7 ft 8$\frac{5}{8}$ in. (92$\frac{5}{8}$ in.). The use of these studs saves on-site labor and gives a clear interior height (finished floor to ceiling) of 8 ft, Figure 15.14. The 8-ft clear height is common in multifamily dwellings, hotels, townhouses, and so on. If 2 × 12 headers are used with these studs, the opening height obtained is 6 ft 10$\frac{1}{2}$ in., which is the standard lintel height for residential doors and windows, Figure 15.15.

Another commonly used special precut length of studs is 104$\frac{5}{8}$ in. (8 ft 8$\frac{5}{8}$ in.), which gives a floor-to-ceiling height of 9 ft. Note that 8-ft and 9-ft floor-to-ceiling heights conform to gypsum board panel sizes.

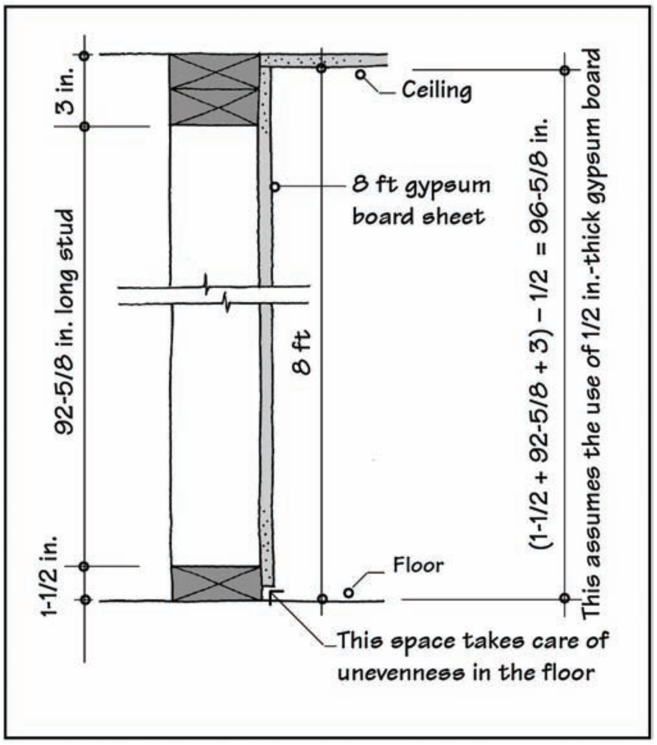
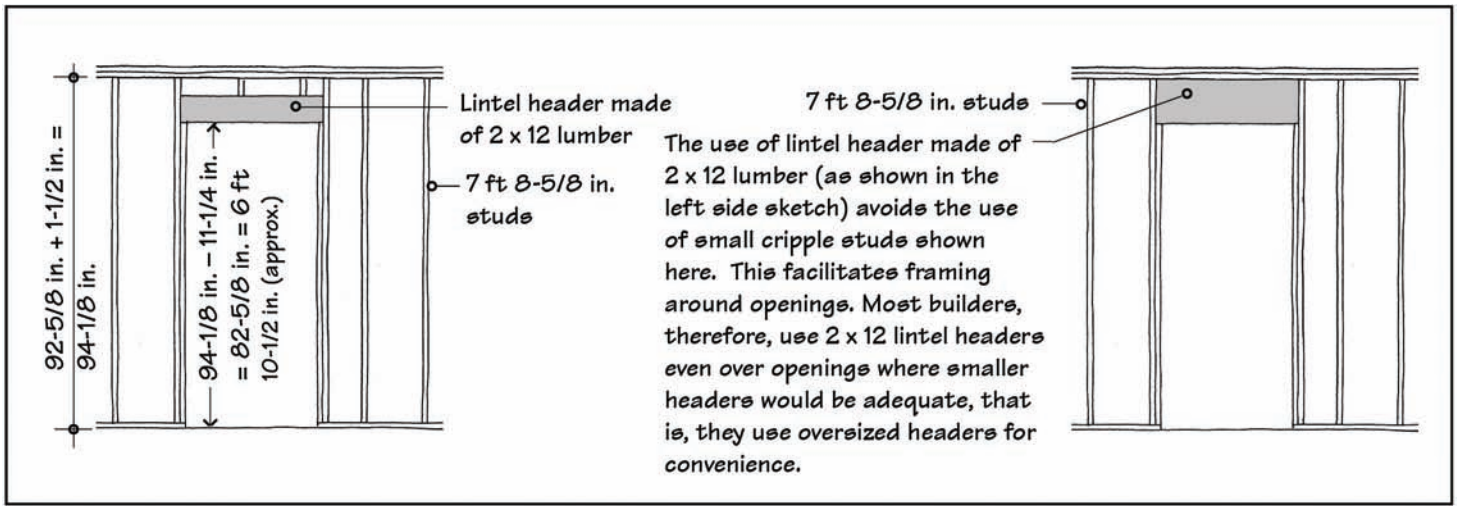

3 in.
92-5/8 in. long stud
1-1/2 in.
Ceiling
8 ft gypsum board sheet
8 ft
Floor
(1-1/2 + 92-5/8 + 3) − 1/2 = 96-5/8 in.
This assumes the use of 1/2 in.-thick gypsum board
This space takes care of unevenness in the floor

FIGURE 15.14 The use of 7-ft 8-$\frac{5}{8}$-in.(92-$\frac{5}{8}$-in.)-high studs.


Lintel header made of 2 x 12 lumber
7 ft 8-5/8 in. studs
7 ft 8-5/8 in. studs
92-5/8 in. + 1-1/2 in. = 94-1/8 in.
94-1/8 in. – 11-1/4 in. = 82-5/8 in. = 6 ft 10-1/2 in. (approx.)

The use of lintel header made of 2 x 12 lumber (as shown in the left side sketch) avoids the use of small cripple studs shown here. This facilitates framing around openings. Most builders, therefore, use 2 x 12 lintel headers even over openings where smaller headers would be adequate, that is, they use oversized headers for convenience.

FIGURE 15.15 The use of oversized headers.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

10. The top plate in a WLF wall generally consists of
  - **a.** one 2-by member.
  - **b.** two 2-by members.
  - **c.** three 2-by members.
  - **d.** any one of the above, depending on architectural considerations.
  - **e.** none of the above.

11. The bottom plate in a WLF wall is called
  - **a.** a sill plate.
  - **b.** a sole plate.
  - **c.** (a) and (b) are synonymous terms.
  - **d.** either (a) or (b), depending on the location of the wall.

12. A sill plate in a WLF wall must be anchored to the foundation with at least
  - **a.** 1-in.-diameter bolts spaced a maximum of 6 ft on centers.
  - **b.** $\frac{3}{4}$-in.-diameter bolts spaced a maximum of 6 ft on centers.
  - **c.** $\frac{1}{2}$-in.-diameter bolts spaced a maximum of 6 ft on centers.
  - **d.** $\frac{1}{4}$-in.-diameter bolts spaced a maximum of 6 ft on centers.
  - **e.** none of the above.

13. A corner made by two WLF walls must have at least
  - **a.** two studs.
  - **b.** three studs.
  - **c.** four studs.
  - **d.** five studs.
  - **e.** six studs.

14. A jack stud is always accompanied by a king stud.
  - **a.** True
  - **b.** False

15. In a WLF wall assembly, a cripple stud is used
  - **a.** at a wall corner.
  - **b.** at a wall T-junction.
  - **c.** at the ends of a wall opening.
  - **d.** above a header or below rough sill.
  - **e.** both (a) and (b).

16. A header over an opening bears directly on
  - **a.** cripple studs.
  - **b.** jack studs.
  - **c.** king studs.
  - **d.** common studs.

17. A precut stud length equal to 7 ft 8$\frac{5}{8}$ in. is commonly used because
  - **a.** it provides a floor-to-ceiling height of 8 ft.
  - **b.** it permits the use of $\frac{1}{2}$-in.-thick gypsum boards.
  - **c.** it permits the use of OSB sheathing; otherwise, more expensive plywood sheathing is needed.
  - **d.** it is more energy efficient.

18. The header over an opening in a wall made of 2 × 6 studs consists of
  - **a.** three 2-by lumber members nailed together.
  - **b.** three 2-by lumber members nailed together with one intervening filler.
  - **c.** three 2-by lumber members nailed together with two intervening fillers.
  - **d.** two 2-by lumber members nailed together with three intervening fillers.
  - **e.** two 2-by lumber members nailed together with two intervening fillers.

15.6 ESSENTIALS OF FLOOR FRAMING

The most crucial aspect of floor framing is the layout of floor joists. It is only after the floor joist layout has been finalized that we can work out the sizes of joists. The initial layout of floor joists is generally prepared by superimposing it on the architectural floor plan. In general, the joists should span between the opposite walls along the shorter of the two spans. When it is not possible to use the walls as supports, an intermediate beam is required to support the joists.

Floor Framing Plan

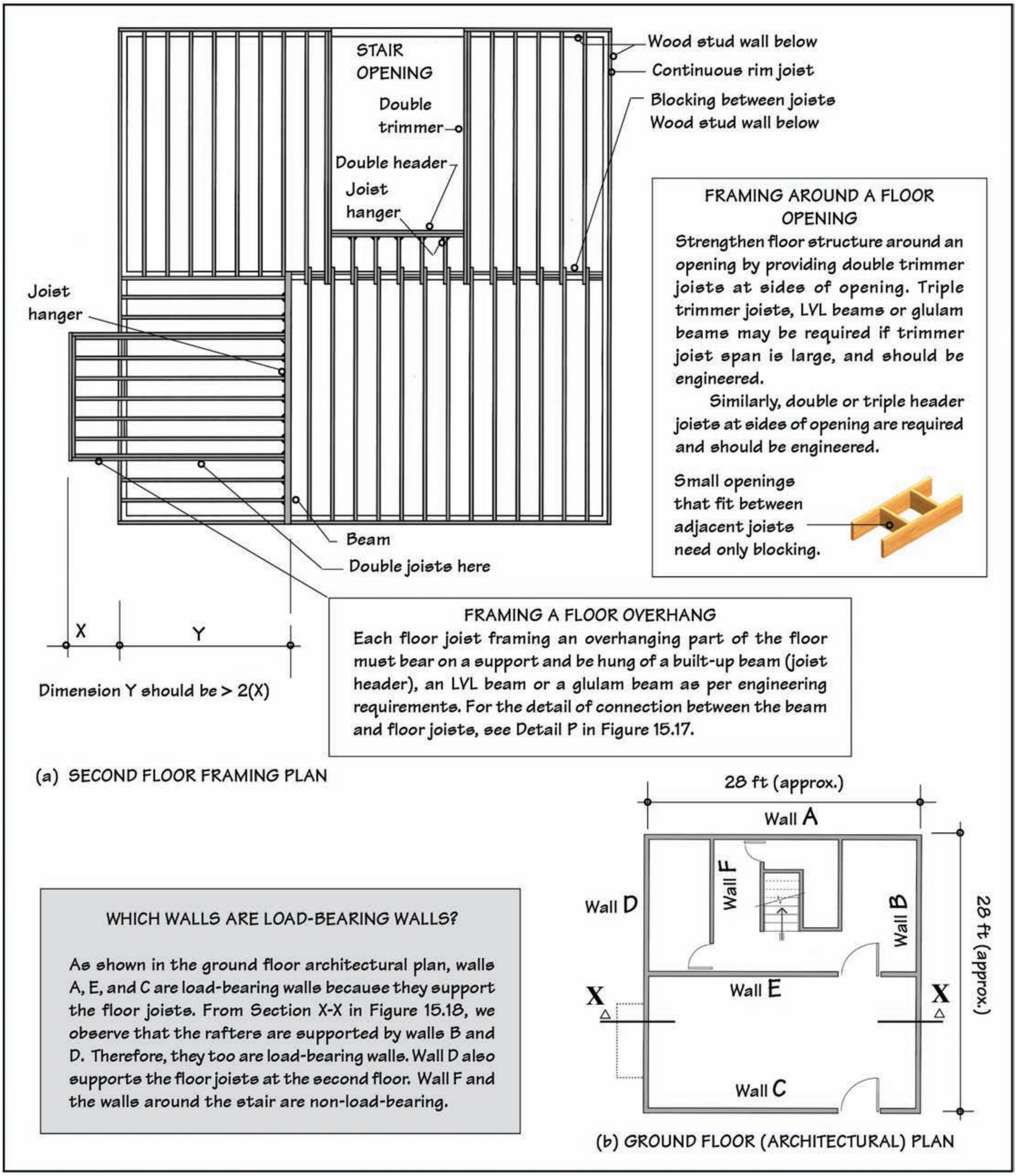
Figure 15.16 shows the layout of the second-floor joists (referred to as the second-floor *framing plan*) of a small (approximately 28 ft × 28 ft) building. The joists have been laid in the direction of the shorter span. However, where there is a cantilevered floor, the joists must be laid along the direction of the overhang.

NOTE

What Is a Load-Bearing Element?

A *load-bearing element* (e.g., a wall) is defined as an element that supports gravity loads other than its self-load. Note that lateral loads are not included in the definition because virtually all building elements (load-bearing or non-load-bearing) have to support some type of lateral load.

For instance, a window (a non-load-bearing element) has to resist lateral loads due to wind and/or earthquake. The same is true of a door or an interior partition wall. An interior partition wall must be designed to resist a minimum lateral load of 5 psf.


STAIR OPENING
Double trimmer
Double header
Joist hanger
Wood stud wall below
Continuous rim joist
Blocking between joists
Wood stud wall below
Joist hanger
Beam
Double joists here
X
Y
Dimension Y should be > 2(X)
28 ft (approx.)
Wall A
Wall D
Wall F
Wall B
Wall E
X
X
Wall C
28 ft (approx.)

FRAMING AROUND A FLOOR OPENING

Strengthen floor structure around an opening by providing double trimmer joists at sides of opening. Triple trimmer joists, LVL beams or glulam beams may be required if trimmer joist span is large, and should be engineered.

Similarly, double or triple header joists at sides of opening are required and should be engineered.

Small openings that fit between adjacent joists need only blocking.

FRAMING A FLOOR OVERHANG

Each floor joist framing an overhanging part of the floor must bear on a support and be hung of a built-up beam (joist header), an LVL beam or a glulam beam as per engineering requirements. For the detail of connection between the beam and floor joists, see Detail P in Figure 15.17.

(a) SECOND FLOOR FRAMING PLAN

WHICH WALLS ARE LOAD-BEARING WALLS?

As shown in the ground floor architectural plan, walls A, E, and C are load-bearing walls because they support the floor joists. From Section X-X in Figure 15.18, we observe that the rafters are supported by walls B and D. Therefore, they too are load-bearing walls. Wall D also supports the floor joists at the second floor. Wall F and the walls around the stair are non-load-bearing.

(b) GROUND FLOOR (ARCHITECTURAL) PLAN

FIGURE 15.16 Second-floor framing plan of a building.

Overhanging joists must bear on a support and be securely connected at the far end (end of the back span) to a wall or a beam. A beam may be a glulam beam or a built-up beam, obtained by nailing two or more 2-by members of the same size as the joists. A built-up beam in this location is referred to as a *joist header*. A glulam beam is commonly used over long spans, and a built-up joist header is used over short spans. In Figure 15.16, a glulam beam has been used.

Joist hangers are required where the joists are hung from a beam or joist header, Figure 15.17. The joist hangers allow the top of the beam and the joists to be at the same elevation.

A framing plan for the ground floor is needed if there is a crawl space or basement floor in the building. Figure 15.18 shows the framing plan of the ground floor of the building in Figure 15.16, assuming an underlying crawl space.

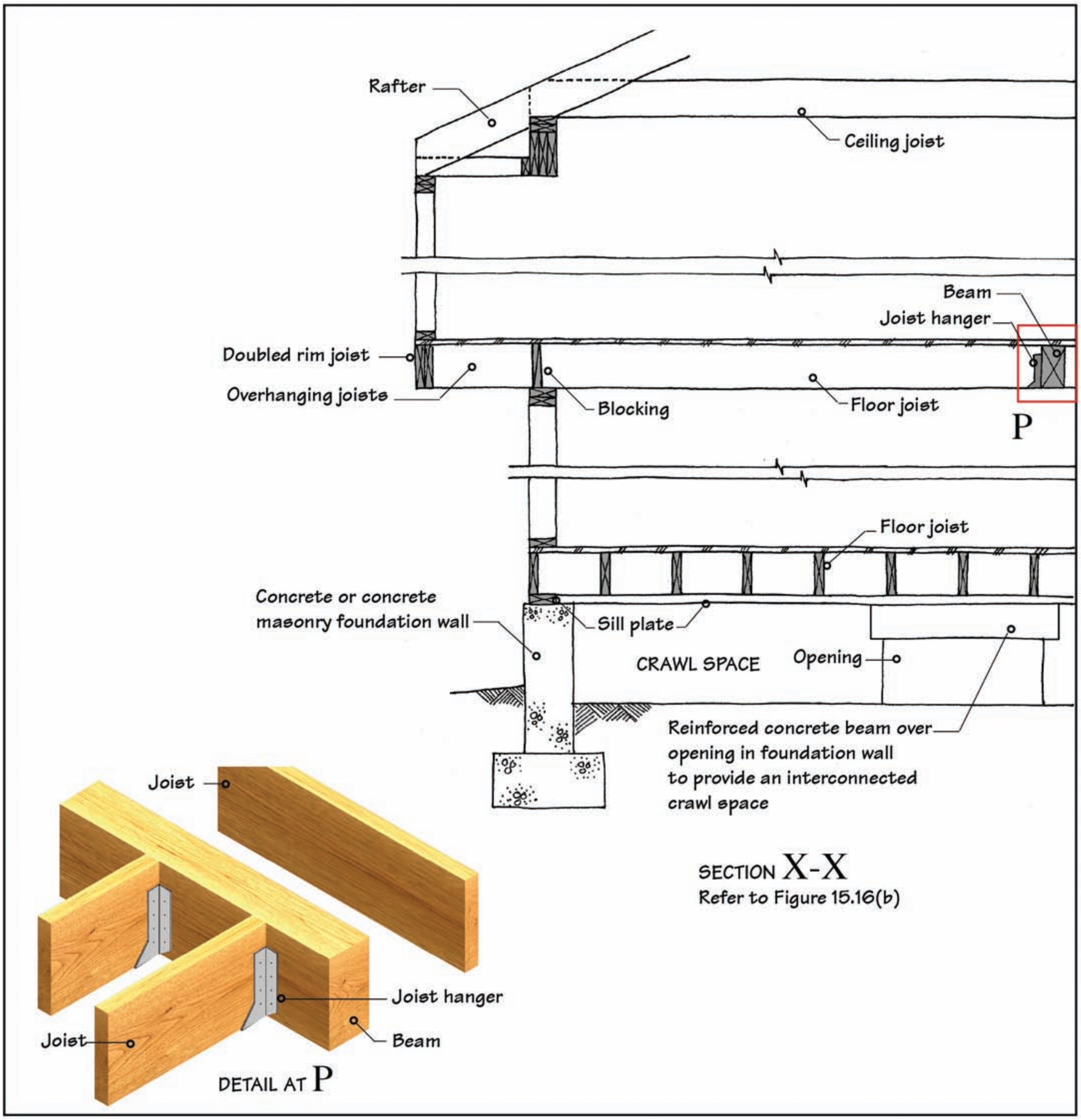

Rafter
Ceiling joist
Beam
Joist hanger
Doubled rim joist
Overhanging joists
Blocking
Floor joist
P
Floor joist
Concrete or concrete masonry foundation wall
Sill plate
CRAWL SPACE
Opening
Reinforced concrete beam over opening in foundation wall to provide an interconnected crawl space
SECTION X-X
Refer to Figure 15.16(b)
Joist
Joist hanger
Beam
Joist
DETAIL AT P

FIGURE 15.17 Section through the building of Figure 15.16. Detail "P" shows the connection between the overhanging floor joists at the second floor and the supporting beam.

SUPPORT FOR LOAD-BEARING AND NON-LOAD-BEARING WALLS

Generally, a load-bearing wall on an upper floor must lie directly over a wall on the lower floor. Additionally, all exterior walls and interior load-bearing walls should be supported on foundation walls or piers, as shown in Figure 15.17.

A non-load-bearing wall on an upper floor may, however, be supported by the floor. Figure 15.19 shows the typical framing enhancement under a non-load-bearing wall that runs parallel to the joists, such as wall F in Figure 15.16. If the wall runs perpendicular to the floor joists, no such reinforcement is generally needed, as shown in Figure 15.20.

ENHANCEMENT OF FLOOR FRAMING

Carefully examine the layout of Figure 15.16. Observe that the joists along the two opposite ends of the cantilevered floor must be doubled. Similarly, the joists framing around an opening (in this case, a stair opening) are also required to be doubled.

Doubling of floor joists (or decreased spacing between joists) may also be needed in areas of the floor that carry excessive load, such as a floor topped with concrete and ceramic tiles, Figure 15.21.

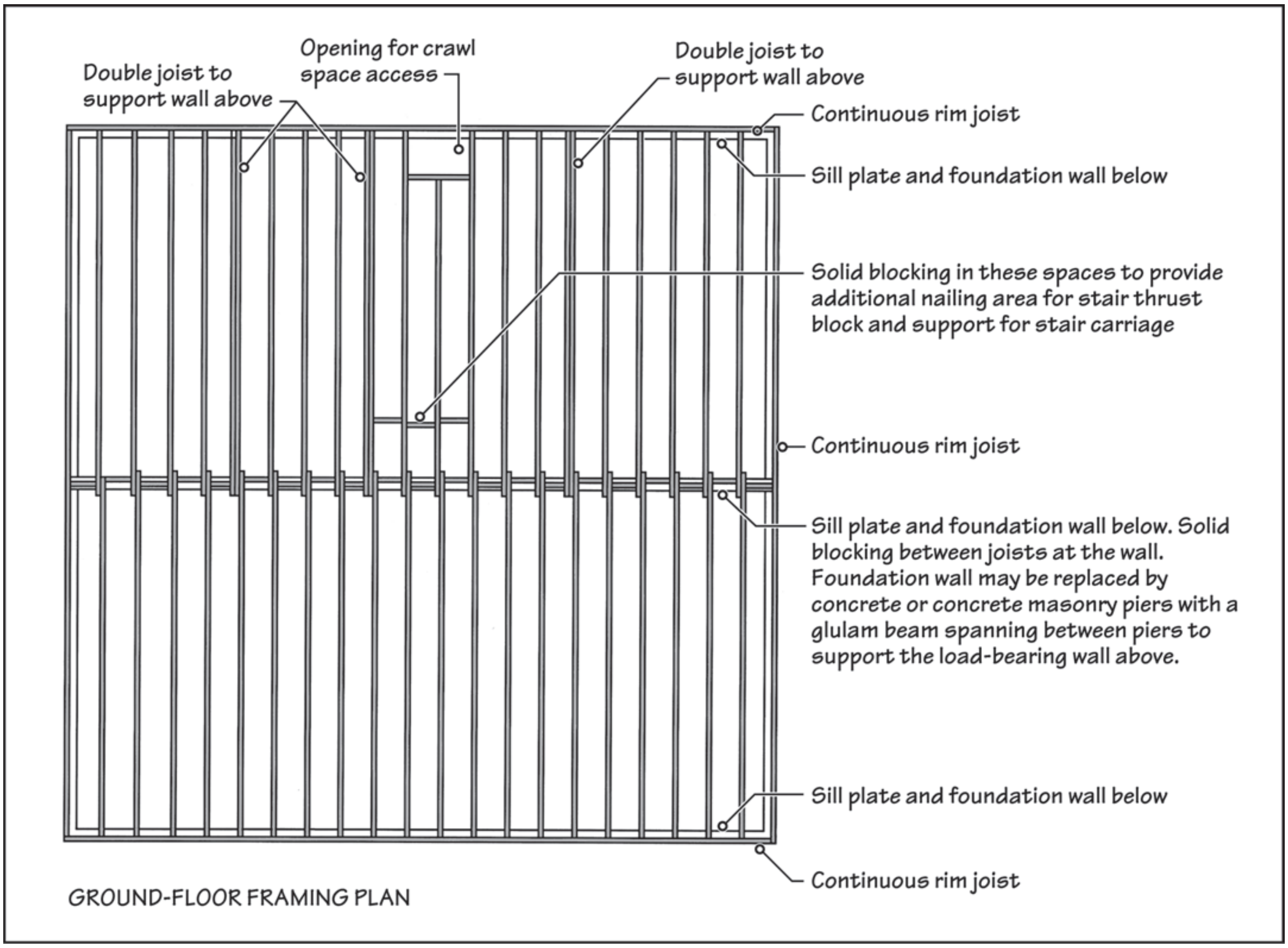

Opening for crawl space access
Double joist to support wall above
Double joist to support wall above
Continuous rim joist
Sill plate and foundation wall below
Solid blocking in these spaces to provide additional nailing area for stair thrust block and support for stair carriage
Continuous rim joist
Sill plate and foundation wall below. Solid blocking between joists at the wall. Foundation wall may be replaced by concrete or concrete masonry piers with a glulam beam spanning between piers to support the load-bearing wall above.
Sill plate and foundation wall below
Continuous rim joist
GROUND-FLOOR FRAMING PLAN

FIGURE 15.18 Ground-floor framing plan of the building in Figure 15.16 (assuming a crawl space below).

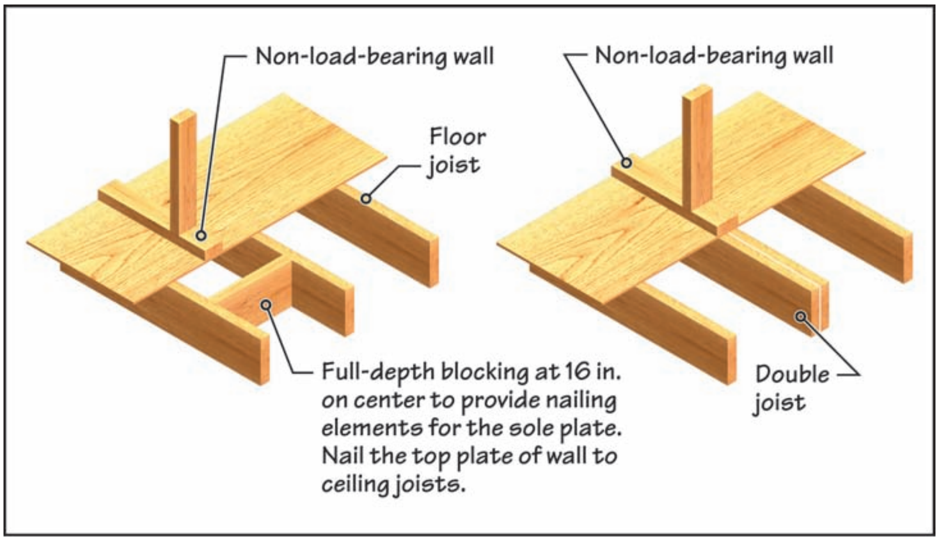

Non-load-bearing wall
Floor joist
Full-depth blocking at 16 in. on center to provide nailing elements for the sole plate. Nail the top plate of wall to ceiling joists.
Non-load-bearing wall
Double joist

FIGURE 15.19 Two alternative ways of supporting a non-load-bearing wall on a wood floor when the wall is parallel to the joists.

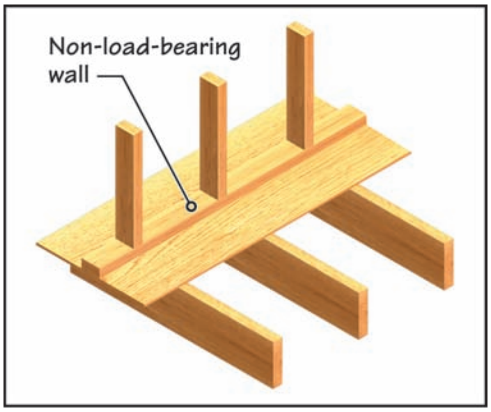
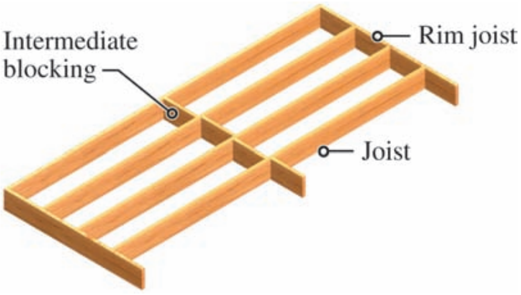

Non-load-bearing wall

FIGURE 15.20 Support for a non-load-bearing wall on a wood floor when the wall is perpendicular to the joists.


Intermediate blocking
Rim joist
Joist

ROLE OF RIM (OR BAND) JOISTS

Because floor joists are slender members, they are prone to lateral buckling (Section 4.9). Rim joists provide lateral restraint to the floor joists, reducing their tendency to buckle as well as connecting the ends of the joists.

For the same reasons, floor joists that have a long span may require intermediate full-depth *blocking* or *diagonal bridging,* Figure 15.22. Generally, intermediate blocking or bridging is required if the floor joist depth is greater than 12 in. (nominal). However, it is prudent to provide rows of blocking or bridging for all floor joists generally at 8 ft on centers.

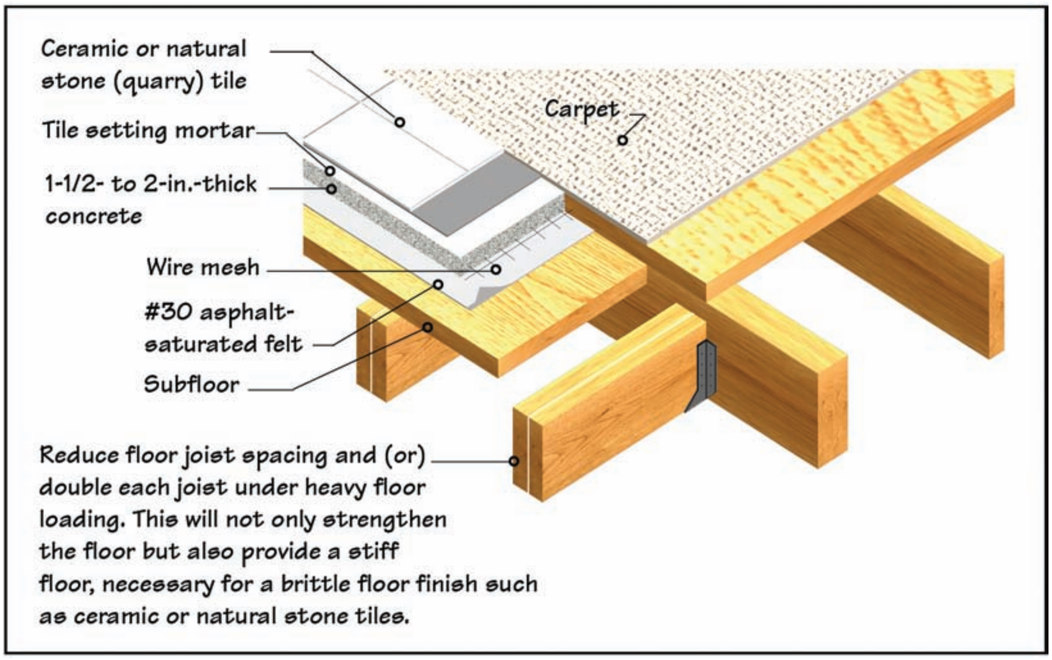

Ceramic or natural stone (quarry) tile
Carpet
Tile setting mortar
1-1/2- to 2-in.-thick concrete
Wire mesh
#30 asphalt-saturated felt
Subfloor
Reduce floor joist spacing and (or) double each joist under heavy floor loading. This will not only strengthen the floor but also provide a stiff floor, necessary for a brittle floor finish such as ceramic or natural stone tiles.

FIGURE 15.21 Strengthening of the floor frame under a heavily loaded part of the floor.

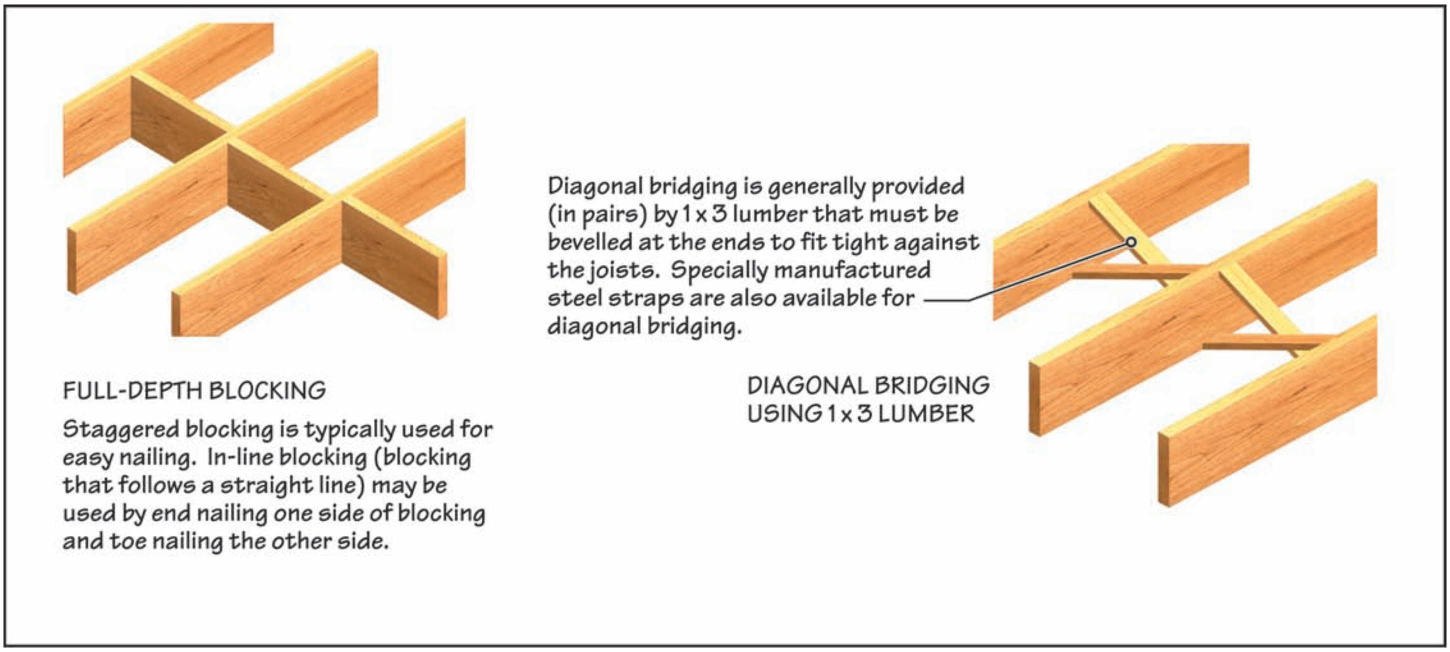

FULL-DEPTH BLOCKING
Staggered blocking is typically used for easy nailing. In-line blocking (blocking that follows a straight line) may be used by end nailing one side of blocking and toe nailing the other side.
Diagonal bridging is generally provided (in pairs) by 1 x 3 lumber that must be bevelled at the ends to fit tight against the joists. Specially manufactured steel straps are also available for diagonal bridging.
DIAGONAL BRIDGING USING 1 x 3 LUMBER

FIGURE 15.22 Two commonly used means of providing intermediate lateral restraint in floor joists.

Diagonal bridging is generally provided through 1 × 3 lumber with bevel-cut ends to fit tight at the joists. Full-depth blocking has the advantage of not requiring bevel-cut ends. It also stiffens the floor and distributes the load between adjacent joists. However, full-depth blocking obstructs pipes running in the space between adjacent joists. Diagonal bridging consisting of metal straps is also available from several manufacturers. It is easier to install than lumber bridging.

STRUCTURAL CONTINUITY IN FLOOR JOISTS AND RIM JOISTS

Floor joists should have continuity, provided either through overlapped ends nailed together at the supporting wall, Figure 15.23(a), or through scabs nailed to butt-jointed ends, Figure 15.23(b). Similar details are used with joists that bear on an underlying beam, Figure 15.23(c). For joists that are connected to a supporting beam with joist hangers, the continuity between joists is provided through the connections, Figure 15.23(d).

A rim joist should also be continuous. Continuity in a rim joist adds to the continuity of the wall's top plate and is typically provided by nailing a 2-by splice member at the joint, Figure 15.24.

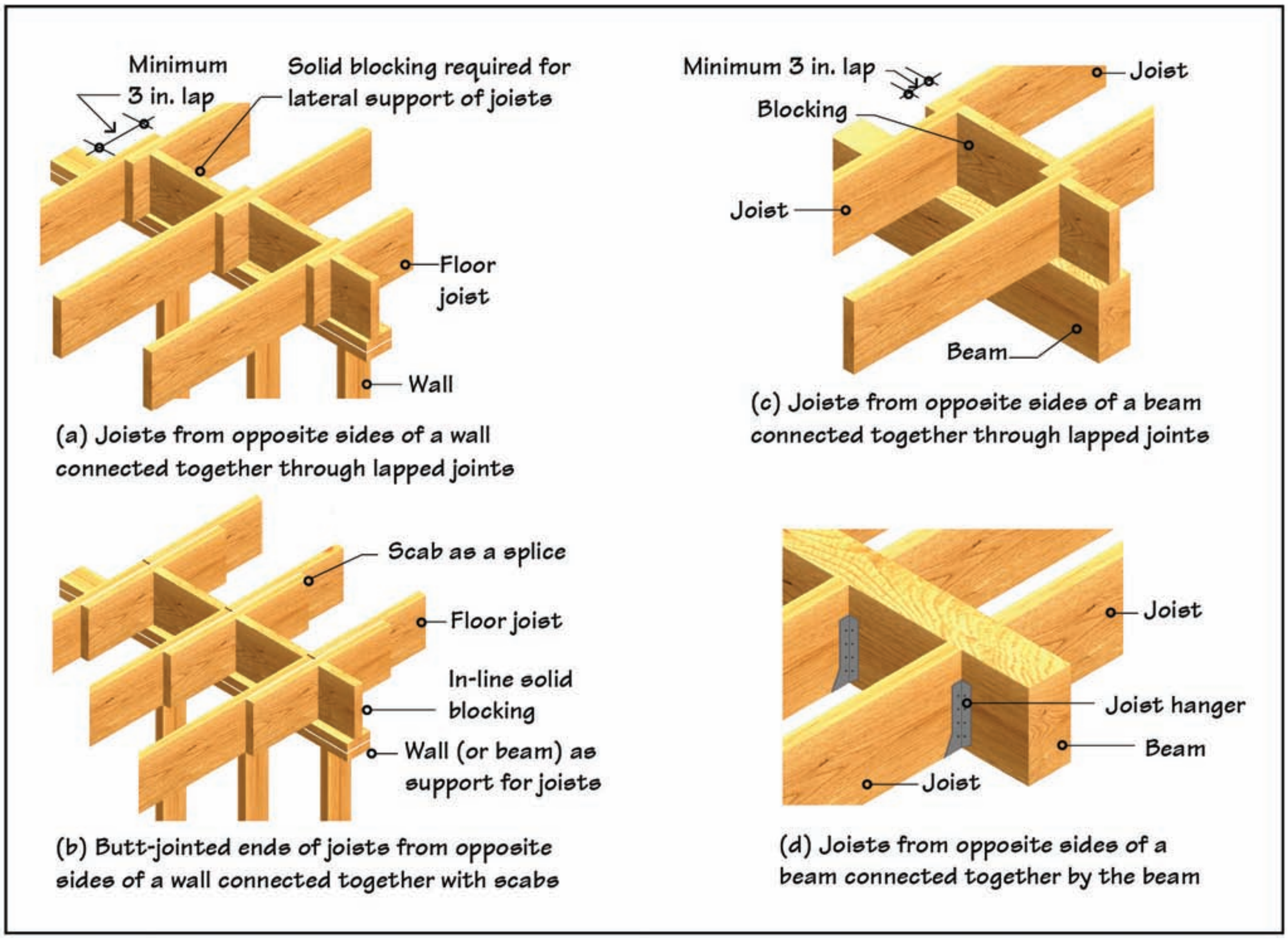

Minimum 3 in. lap
Solid blocking required for lateral support of joists
Floor joist
Wall
(a) Joists from opposite sides of a wall connected together through lapped joints
Minimum 3 in. lap
Joist
Blocking
Joist
Beam
(c) Joists from opposite sides of a beam connected together through lapped joints
Scab as a splice
Floor joist
In-line solid blocking
Wall (or beam) as support for joists
(b) Butt-jointed ends of joists from opposite sides of a wall connected together with scabs
Joist
Joist hanger
Beam
Joist
(d) Joists from opposite sides of a beam connected together by the beam

FIGURE 15.23 Details of floor joists resting on an intermediate support.

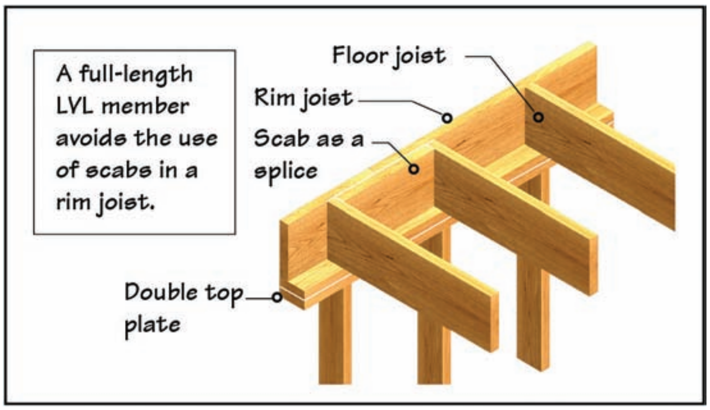

A full-length LVL member avoids the use of scabs in a rim joist.
Floor joist
Rim joist
Scab as a splice
Double top plate

FIGURE 15.24 Detail of a splice-connected rim joist.

15.7 ROOF TYPES AND ROOF SLOPE

The roof of a WLF building is generally sloped. The more commonly used roof shapes are gable, hip, and shed roofs. Often these roof types are used in combination, Figure 15.25. Figure 15.25 also provides an introduction to some of the roof vocabulary.

The slope of a roof is not expressed in degrees but as a rise-to-run ratio. In this expression, the run is generally kept at a constant value of 12. Thus, a roof slope is expressed as 2:12, $2\frac{1}{2}$: 12, 5:12, 6:12, and so on. The greater the rise, the greater the roof slope. As we will observe in Chapter 33, the roofing industry divides roofs into two types based on roof slope:

- Low-slope roof
- Steep roof

A low-slope roof is a roof whose slope is less than 3:12. A steep roof has a slope of greater than or equal to 3:12. Using a 3:12 roof slope as the dividing line is based on structural considerations, as explained later in this chapter.

An additional basis for the dividing line is roof cover considerations. Several asphalt shingle manufacturers do not warrant the use of their product on a roof with a slope of less than 3:12.

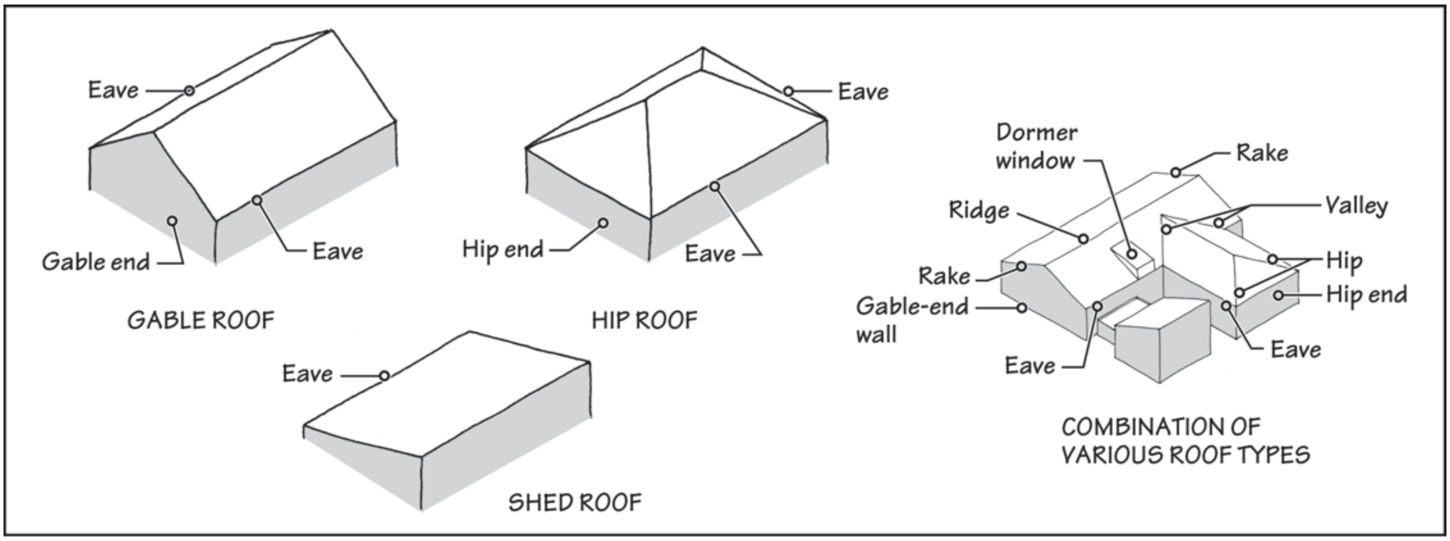


FIGURE 15.25 Commonly used roof shapes and roof-related terminology.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

19. In a WLF building, a floor framing plan indicates
- **a.** the layout of studs and their spacing.
- **b.** the layout of studs and exterior wall sheathing.
- **c.** the layout of floor joists and blocking.
- **d.** the layout of floor joists, floor beams, and blocking.
- **e.** the layout of floor beams, studs, and wall sheathing.

20. A non-load-bearing wall in a building is one that supports the loads from the roof but not from any floor.
- **a.** True
- **b.** False

21. The primary purpose of full-depth blocking in a floor frame is to
- **a.** reduce compressive stresses in floor joists.
- **b.** prevent buckling of floor joists.
- **c.** reduce tensile stresses in floor joists.
- **d.** give additional nailing surface for a gypsum board ceiling.
- **e.** give additional nailing surface for floor sheathing.

22. Blocking between floor joists is required where
- **a.** the joists bear on a wall.
- **b.** the joists bear on a beam.
- **c.** the joists are hung on a beam using joist hangers.
- **d.** all of the above.
- **e.** both (a) and (b).

23. A floor in a WLF building that supports a non-load-bearing wall generally requires no additional strengthening or stiffening when
- **a.** the wall runs parallel to floor joists.
- **b.** the wall runs perpendicular to floor joists.

24. A roof with gable ends on both sides in a rectangular building has
- **a.** eaves on all four sides.
- **b.** eaves on three sides.
- **c.** eaves on two sides.
- **d.** eave on one side.
- **e.** no eaves.

25. A rectangular roof with hip ends on two sides has
- **a.** eaves on all four sides.
- **b.** eaves on three sides.
- **c.** eaves on two sides.
- **d.** eave on one side.
- **e.** no eaves.

26. In the building industry, the slope of a roof is generally expressed
- **a.** in degrees.
- **b.** in radians.
- **c.** as a rise-to-run ratio.
- **d.** as a run-to-rise ratio.
- **e.** none of the above.

15.8 ESSENTIALS OF ROOF FRAMING

The roof framing of a typical WLF building consists either of trusses or of rafter-and-ceiling joist assemblies. Theoretically, there is little difference between them, except that a truss is a shop-fabricated, multitriangle frame and a rafter-and-ceiling-joist assembly is a site-fabricated, single-triangle frame.

In a rafter-joist assembly, the rafters rest on the walls at one end and are connected to the opposite rafters at the ridge. The connection between the two rafters is made through a continuous *ridge board* that runs perpendicular to the rafters.

A ridge board is generally a 2-by member that must extend from the top edge to the bottom edge of the rafter (or a little below), Figure 15.26. It has no structural function except to align the rafter ends in a straight line at the top. That is why the codes only require a 1-by member, although a 2-by member is generally used as the ridge board. Many framers use an LVL member to ensure a continuous, straight ridge.

Each rafter pair (connected at the ridge) must be tied together at the bottom to resist the outward thrust created by the gravity loads on the roof. In a typical WLF roof, this tie also

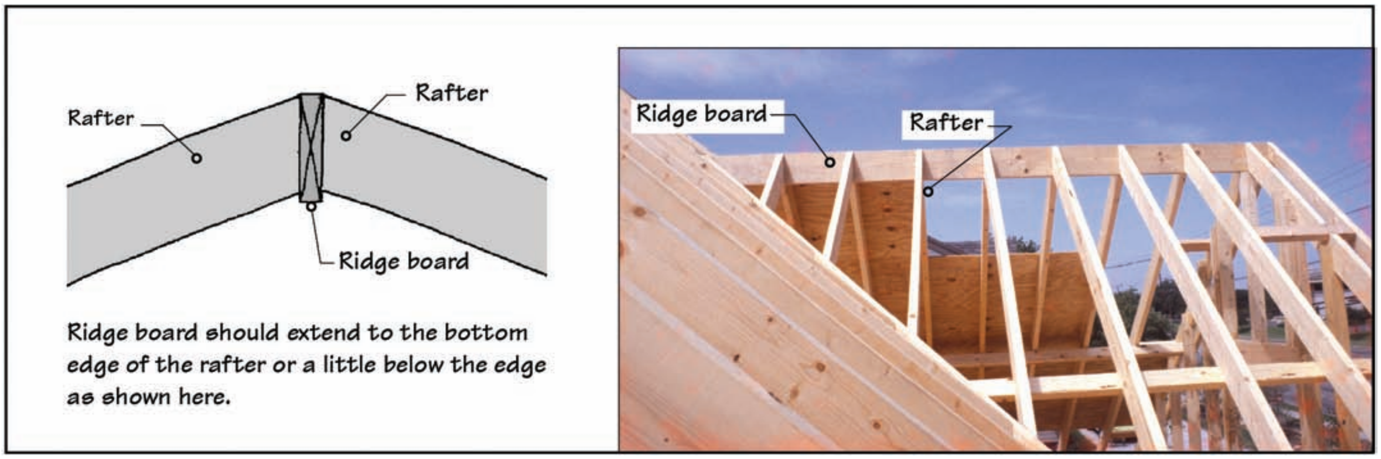

Rafter
Rafter
Ridge board
Ridge board should extend to the bottom edge of the rafter or a little below the edge as shown here.
Ridge board
Rafter

FIGURE 15.26 Ridge board and rafters.

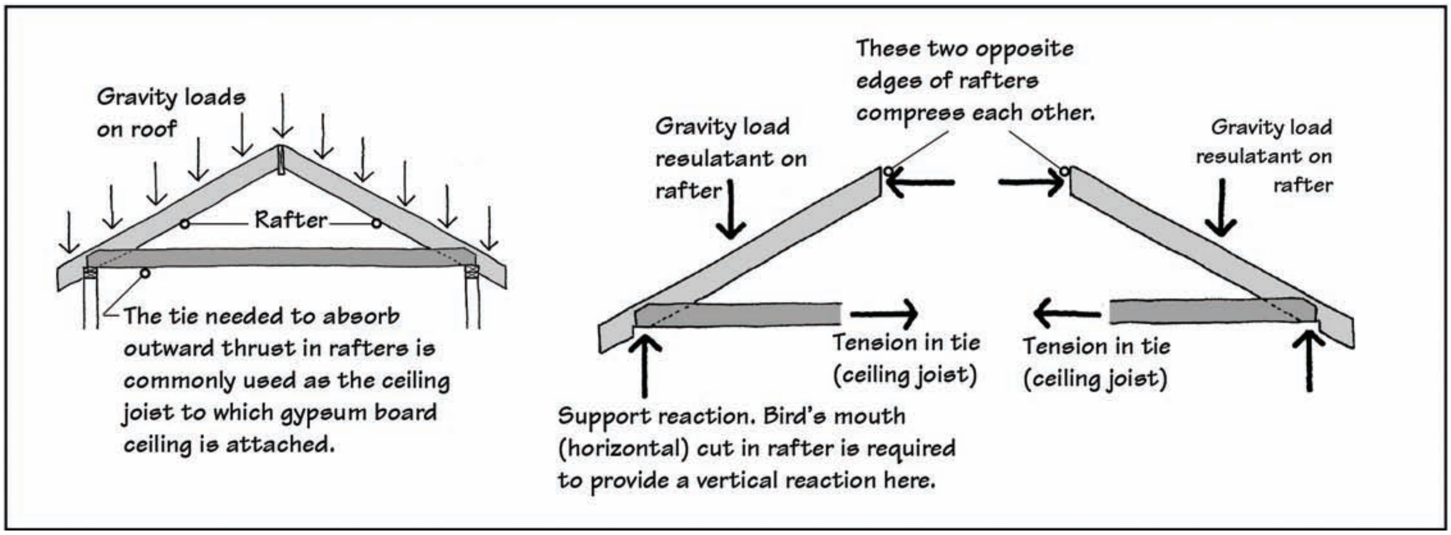
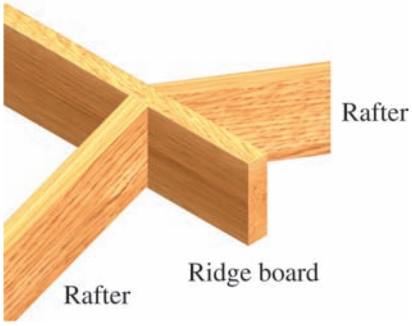

Gravity loads on roof
Rafter
The tie needed to absorb outward thrust in rafters is commonly used as the ceiling joist to which gypsum board ceiling is attached.
These two opposite edges of rafters compress each other.
Gravity load resultant on rafter
Gravity load resultant on rafter
Tension in tie (ceiling joist)
Tension in tie (ceiling joist)
Support reaction. Bird's mouth (horizontal) cut in rafter is required to provide a vertical reaction here.

FIGURE 15.27 Forces created by gravity loads in a rafter couple and ceiling-joist assembly.


Rafter
Ridge board
Rafter

functions as the ceiling joist, Figure 15.27. The rafter pair and the ceiling joist thus make a stable triangular frame, which rests on two opposite supports and delivers a vertical load at the supports with no lateral thrust.

To deliver the load vertically at the support, each rafter is cut to have a horizontal bearing on the supporting walls. Each rafter is, therefore, specially notched near the bottom. This notch is referred to as a *bird's mouth,* Figure 15.28. The horizontal part of the bird's mouth should equal the width of the supporting wall (including the thickness of sheathing) to ensure that the wall sheathing engages the top plate fully. If the sheathing is applied to the wall after the rafters are in place, it must be cut around the rafters.

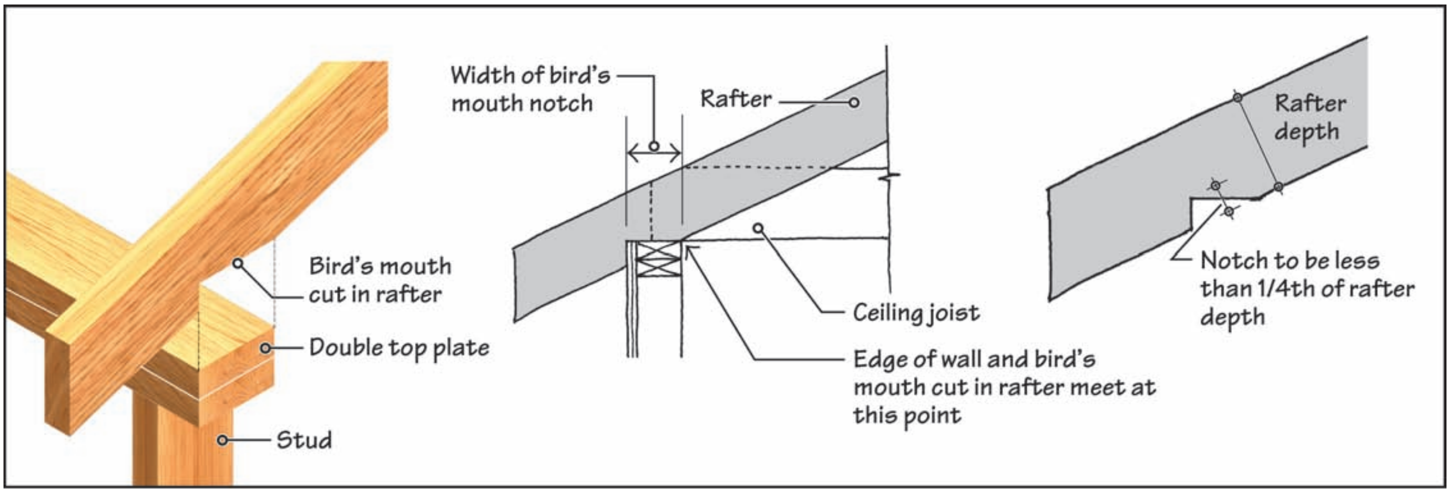

Bird's mouth cut in rafter
Double top plate
Stud
Width of bird's mouth notch
Rafter
Ceiling joist
Edge of wall and bird's mouth cut in rafter meet at this point
Rafter depth
Notch to be less than 1/4th of rafter depth

FIGURE 15.28 Bird's mouth cut in a rafter.

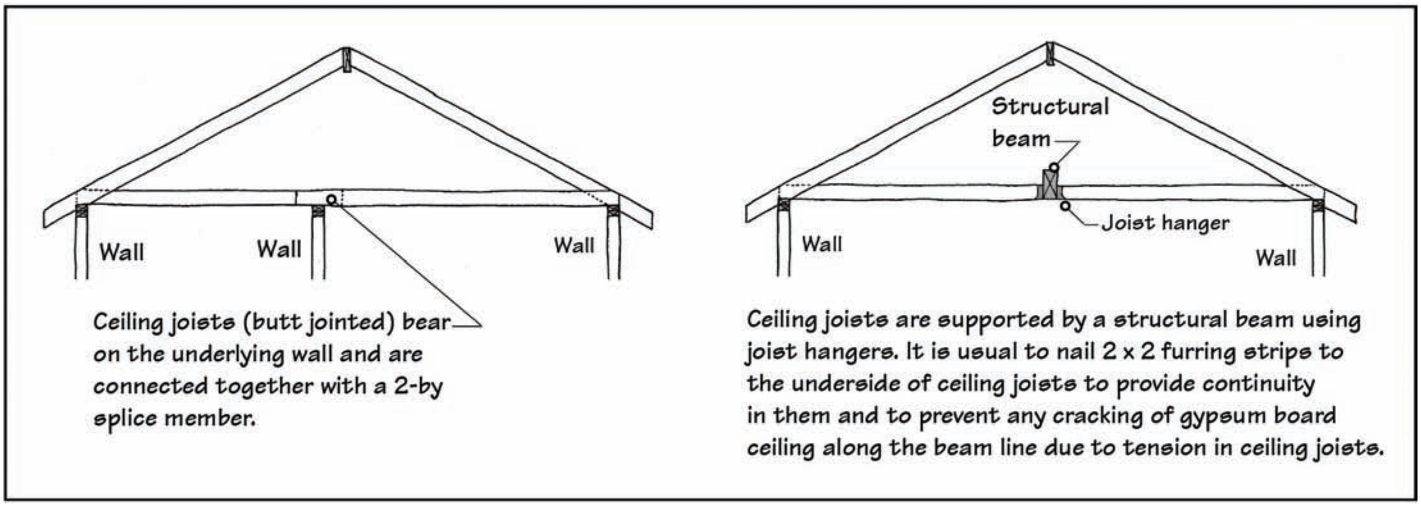
SUPPORT FOR CEILING JOISTS

Because the distance between the supporting walls is usually too large to allow the use of one-piece members as ceiling joists, the ceiling joists are generally two-piece members connected together at an intermediate support. The intermediate support is necessary because the ceiling joists are subjected not only to tension but also to bending due to gravity loads from the attic. The intermediate support is usually an underlying wall, Figure 15.29. If a wall is not available, a beam should be introduced. Alternatively, prefabricated roof trusses may be used, which do not need intermediate supports.

PREFABRICATED TRUSSES AS AN ALTERNATIVE TO A RAFTER-JOIST ASSEMBLY

Wood trusses are an alternative to a stick-built rafter-joist assembly. Their use is particularly attractive for single-family dwellings in regions where prefabrication is more economical because of the climate's severity and/or the higher labor costs.

Because of the length limitations of sawn lumber, a rafter-joist assembly has limited span capabilities. When the width of the building is large (typically greater than 35 ft), the use of trusses is a more viable solution for roof framing, Figure 15.30. Wood trusses are, therefore, a norm in wood frame commercial and multifamily residential buildings. Truss manufacturers provide all the necessary engineering and details that should be used with their trusses.



Ceiling joists (butt jointed) bear on the underlying wall and are connected together with a 2-by splice member.

Ceiling joists are supported by a structural beam using joist hangers. It is usual to nail 2 x 2 furring strips to the underside of ceiling joists to provide continuity in them and to prevent any cracking of gypsum board ceiling along the beam line due to tension in ceiling joists.

FIGURE 15.29 Ceiling-joist support.

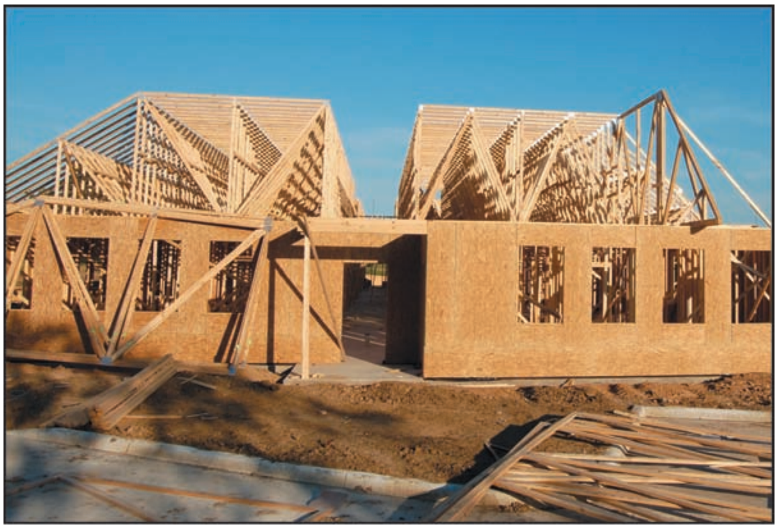


FIGURE 15.30 Prefabricated wood trusses are commonly used in buildings where roof spans are large. Prefabrication reduces on-site labor and hence makes trusses a popular alternative in regions with unfavorable weather conditions or high labor costs.

15.9 VAULTED CEILINGS

The rafter-and-ceiling-joist assembly described previously works only if the roof slope is greater than 3:12. If the slope is less than 3:12, the tension in ceiling joists becomes too large to be handled by conventional 2-by members. In such a case, the ridge board must be replaced by a *ridge beam*. A ridge beam is a structural member, unlike a ridge board. The rafters bear on the ridge beam at the top and on the supporting walls at the eave.

Such an assembly, consisting of two opposite rafters and the ridge beam, creates no outward thrust in the rafters under gravity loads. Consequently, there is no need for Ceiling-joist ties. The gypsum board ceiling in such a roof may be attached directly to the rafters and ridge beam, and/or the ridge beam may remain exposed. Such a ceiling is referred to as a *cathedral ceiling* or a *vaulted ceiling*, Figure 15.31. A vaulted ceiling may also be used with a roof slope greater than 3:12.

15.10 SHEATHING APPLIED TO A FRAME

The wall, floor, and roof frames must be covered with a sheathing material. Sheathing (generally a panel material) serves both structural and nonstructural functions.

WALL SHEATHING AND LATERAL BRACING OF THE FRAME

Wall sheathing furnishes a base over which exterior wall finishes are applied. It also provides a nailing base for an air-weather retarder. Structurally, wall sheathing integrates the studs into a composite wall system. It also provides bracing to the frame against lateral loads.

The most commonly used material for exterior wall sheathing (and bracing) is OSB. However, plywood, gypsum sheathing, and several other panel materials (including rigid foam insulation) are acceptable bracing alternatives. The minimum area of the exterior wall that must be covered with bracing material is a function of the number of stories of the building and the intensity of the lateral load. However, as shown in Figure 14.29, the walls of most WLF buildings are often fully sheathed with OSB (excluding the openings), which generally exceeds the minimum bracing requirement.

An alternative to panel bracing is a diagonal let-in brace, Figure 15.32. This consists of a 1 × 4 lumber member fastened to studs that are notched to receive the brace. The angle of

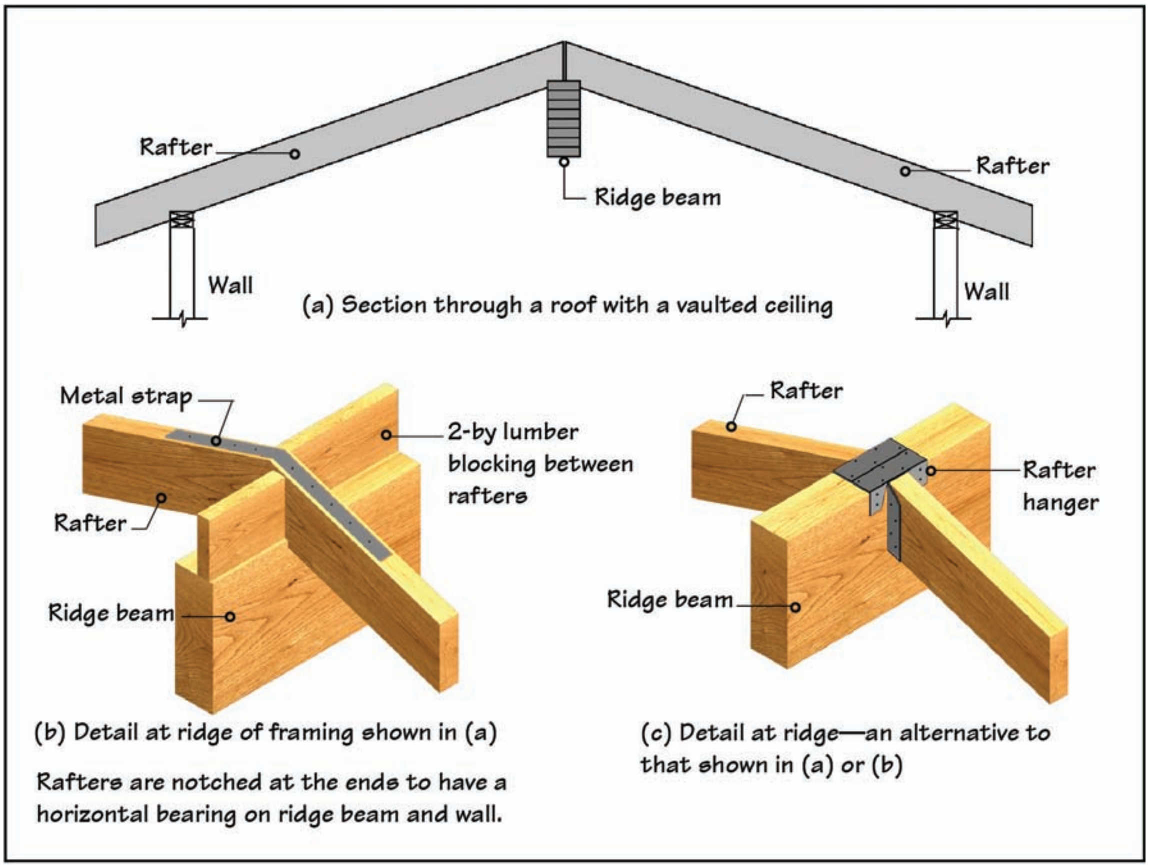

Rafter
Ridge beam
Rafter
Wall
Wall
(a) Section through a roof with a vaulted ceiling
Metal strap
2-by lumber blocking between rafters
Rafter
Ridge beam
(b) Detail at ridge of framing shown in (a)
Rafters are notched at the ends to have a horizontal bearing on ridge beam and wall.
Rafter
Rafter hanger
Ridge beam
(c) Detail at ridge—an alternative to that shown in (a) or (b)

FIGURE 15.31 If the rafters are supported on a (structural) ridge beam, ceiling joists are not required to absorb the lateral thrust. Such a roof system is called a *vaulted* (or *cathedral*) *ceiling*.

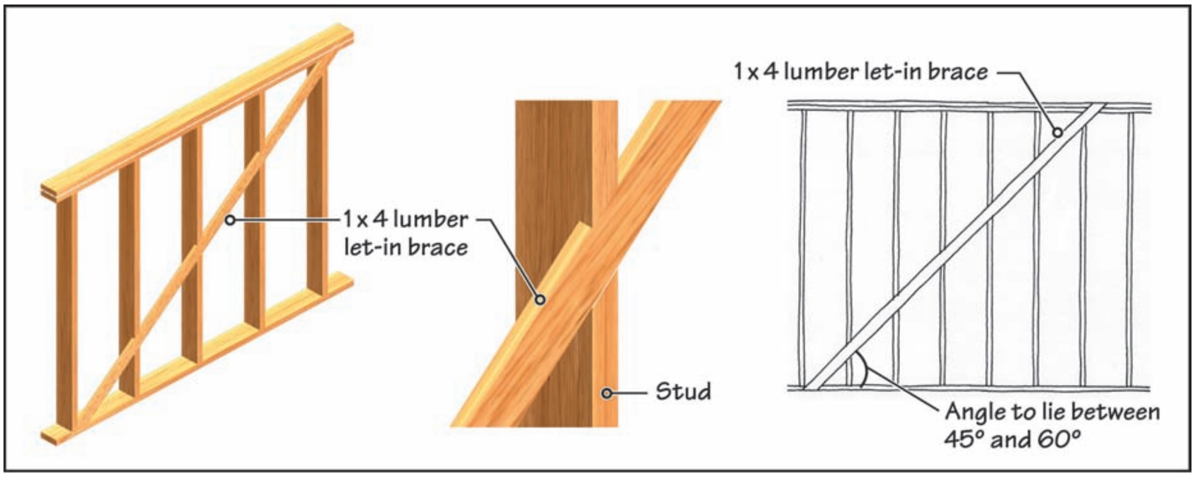


FIGURE 15.32 Lumber let-in brace.

the brace with the horizontal should lie between 45° and 60°. A steel angle let-in brace may also be used in place of a lumber let-in brace. This requires only a small slit cut into the studs.

The bracing strength of a let-in brace (wood or steel) is much smaller than that of OSB panel bracing. Therefore, the use of a let-in brace is generally limited to situations where the lateral loads are small.

WLF buildings that have a relatively large footprint may require bracing in the interior walls in addition to the bracing provided in exterior walls. Interior-wall bracing can be provided by sheathing the interior walls on both sides with OSB and covering them with gypsum board. Alternatively, 2-by lumber (blocking) members placed diagonally through the wall may be used to obtain an interior braced wall, Figure 15.33.

FLOOR SHEATHING

Floor sheathing (also called a *subfloor*) is a structural element because it transfers floor dead and live loads to the joists. Floor sheathing also provides diaphragm action in resisting lateral loads. The most commonly used material for a subfloor is OSB panels, generally used in 4-ft × 8-ft dimensions. Panels must be laid with the 8-ft dimensions perpendicular to the joists, Figure 15.34. Two types of subfloor panels are used, depending on the profile of the long (8-ft) edges:

- All four panel edges have a straight profile.
- Two long edges have a tongue-and-groove profile, whereas the other two edges are straight (Section 14.8).

If carpet is used as the floor finish, straight-edge subfloor panels require blocking along the long edges. Resilient floor finishes (such as vinyl or linoleum tiles or sheets) generally require a smooth underlayment over an OSB subfloor (Chapter 36). When a floor underlayment is used, blocking of the long edges of the subfloor is generally not required. Blocking is also not required if tongue-and-groove panels are used for the subfloor.

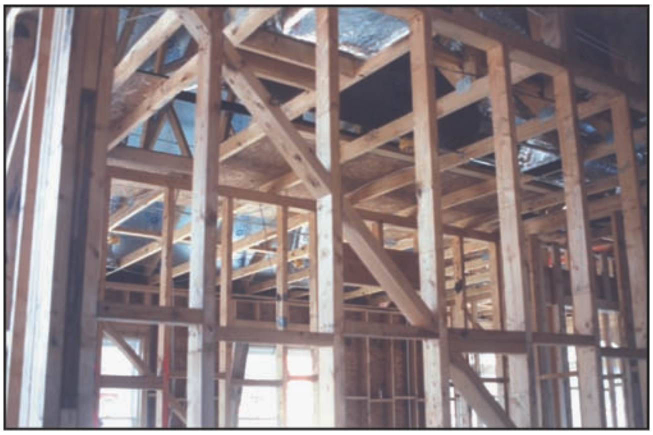


FIGURE 15.33 Diagonal bracing of an interior wall with 2-by lumber members.

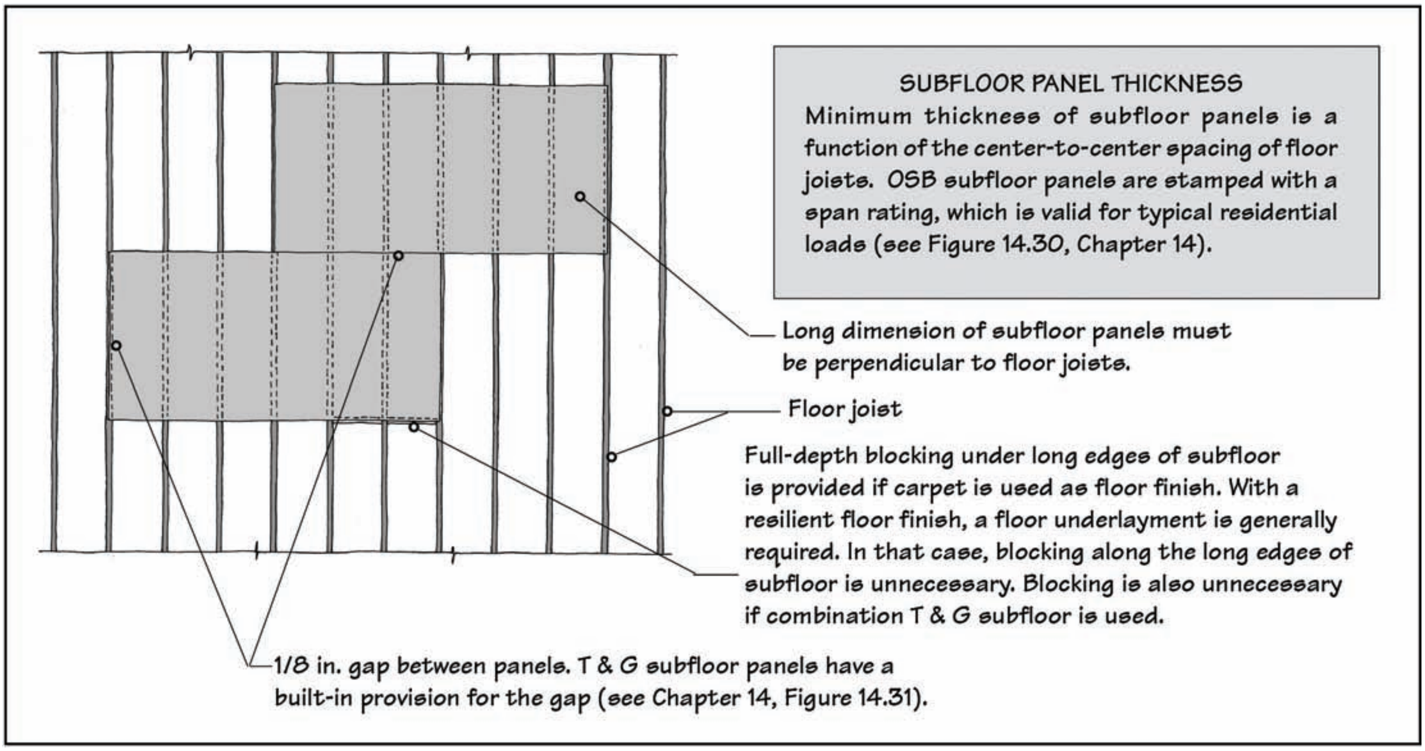

SUBFLOOR PANEL THICKNESS
Minimum thickness of subfloor panels is a function of the center-to-center spacing of floor joists. OSB subfloor panels are stamped with a span rating, which is valid for typical residential loads (see Figure 14.30, Chapter 14).
Long dimension of subfloor panels must be perpendicular to floor joists.
Floor joist
Full-depth blocking under long edges of subfloor is provided if carpet is used as floor finish. With a resilient floor finish, a floor underlayment is generally required. In that case, blocking along the long edges of subfloor is unnecessary. Blocking is also unnecessary if combination T & G subfloor is used.
1/8 in. gap between panels. T & G subfloor panels have a built-in provision for the gap (see Chapter 14, Figure 14.31).

FIGURE 15.34 Subfloor requirements.

ROOF SHEATHING

Like floor sheathing, roof sheathing is also a structural component, and OSB panels are most commonly used. The thickness of panels is based on their span rating. Roof sheathing panels do not require blocking, but metal edge clips (generally H-shaped) are used along the long (8-ft) edges to join adjacent panels, Figure 15.35. The clips automatically leave a gap of $\frac{1}{8}$ in. between panels and allow the edges of panels to expand.

15.11 EQUALIZING CROSS-GRAIN LUMBER DIMENSIONS

In Section 15.2, reference was made to the moisture-related dimensional instability of cross-grain lumber. In a WLF building, cross-grain lumber is present in floor and wall frames. In the walls, only the top and bottom plates constitute cross-grain lumber. In the floors, floor joists and supporting beams constitute cross-grain lumber.

It is usually not possible to reduce cross-grain lumber dimensions in a building. All that can be done is to equalize cross-grain lumber dimensions throughout the structural frame so that the entire frame moves as a unit. Unequal cross-grain lumber dimensions lead to differential swelling and shrinkage, creating bending of framing members, which can crack brittle interior (gypsum) finishes. It may also lead to squeaking floors.

Consider the building in Figure 15.36, where a steel beam has been used in the basement to support the overlying floor and wall. This is a commonly used detail because the steel beam is unaffected by moisture changes. The provision of a 2-by member directly above the steel beam matches the sill plate over the foundation wall, equalizing the cross-grain lumber dimension. It also provides a nailing surface for the joists, Figure 15.37.

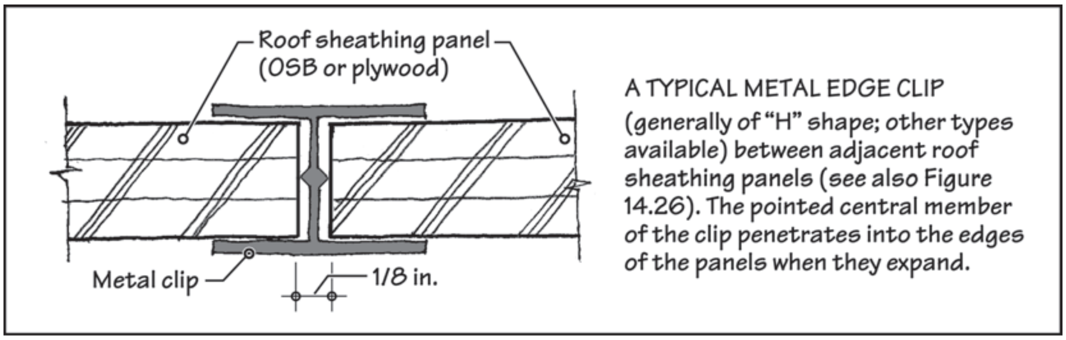

Roof sheathing panel (OSB or plywood)
Metal clip
1/8 in.
A TYPICAL METAL EDGE CLIP (generally of "H" shape; other types available) between adjacent roof sheathing panels (see also Figure 14.26). The pointed central member of the clip penetrates into the edges of the panels when they expand.

FIGURE 15.35 Clip between adjacent roof sheathing panels.

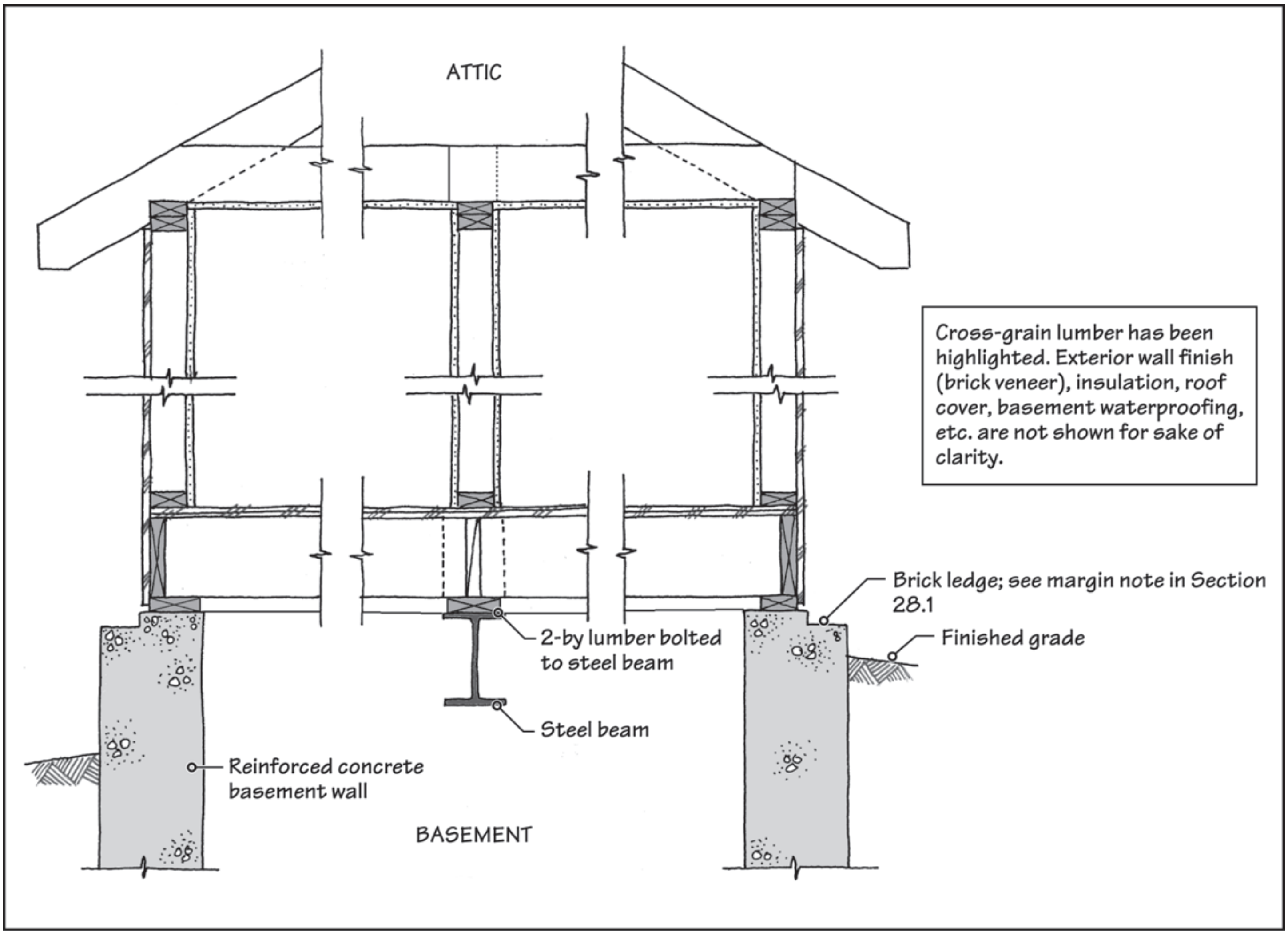

ATTIC
Cross-grain lumber has been highlighted. Exterior wall finish (brick veneer), insulation, roof cover, basement waterproofing, etc. are not shown for sake of clarity.
Brick ledge; see margin note in Section 28.1
Finished grade
2-by lumber bolted to steel beam
Steel beam
Reinforced concrete basement wall
BASEMENT

FIGURE 15.36 Equalizing cross-grain lumber dimensions in a WLF building using a steel beam.

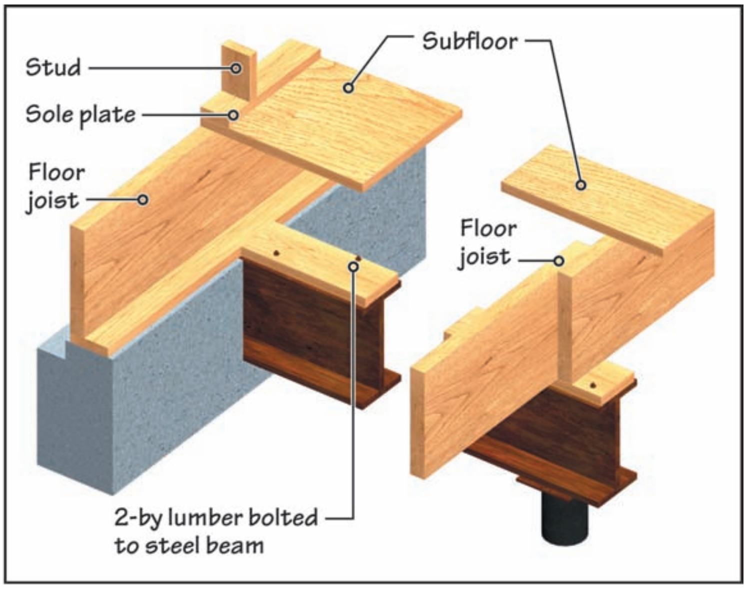

Stud
Sole plate
Subfloor
Floor joist
Floor joist
2-by lumber bolted to steel beam

FIGURE 15.37 Floor-level detail of the structure in Figure 15.36.

15.12 WOOD LIGHT FRAME AND THE INTERNATIONAL BUILDING CODE

A building of construction Type III(A), III(B), V(A), or V(B) is generally constructed of wood light frame (WLF), that is, using 2-by lumber framing members. In Type V(A), all structural assemblies (interior and exterior bearing walls, floors, roofs, and interior partitions) are required to be minimum 1-h fire rated. A 1-h rating is typically achieved by covering the wood frame with $\frac{5}{8}$-in.-thick type X gypsum board on both sides.

Type V(B) is unprotected WLF construction, implying that the fire rating of various structural assemblies is less than 1 h. Thus in a typical Type V(B) assembly, WLF members are covered with $\frac{1}{2}$-in.-thick type R gypsum board on both sides, resulting in a fire rating of approximately 30 min.

Type III(A) is similar to Type V(A) except that: (a) the exterior walls (bearing and non-bearing) must be of noncombustible materials, and (b) the exterior bearing walls must have a minimum 2-h fire rating. In Type III(B), all assemblies may be unprotected except that the exterior walls must meet the same requirements as for Type III(A), that is, the use of noncombustible materials in both bearing and non-bearing walls and a minimum 2-h rating for the bearing walls. The "noncombustible material" requirement for the exterior walls of Type III(A) and Type III(B) is generally accomplished by using fire-retardant-treated (FRT) wood members.

The maximum number of stories permitted by the code for a building of Type V(A), V(B), III(A), or III(B) is fairly limited even when the building is fully sprinklered. For example, for a fully sprinklered, R-2 occupancy building (apartment buildings, dormitories, etc.) in Type V(B) construction, the maximum permissible number of stories is three. If the type of construction for the same building is Type V(A), the maximum number of stories is four. These facts and the corresponding maximum permissible heights are shown in Figure 15.38.

15.13 BUILDING TALLER WITH WOOD LIGHT FRAME

The story limitations of a building can be somewhat relaxed by invoking the *horizontal building separation allowance* given in Section 510 of the International Building Code (IBC). This allowance states that if a horizontal separation assembly (i.e., an intermediate floor) with a minimum 3-h fire rating is provided in a building, it will create two totally independent buildings: one above the horizontal separation and the other below it.

In other words, a horizontal separation functions like a fire wall. Whereas a fire wall divides a building into two independent buildings placed side-by-side, a horizontal separation yields two independent buildings, stacked vertically. The two horizontally separated buildings are entitled to their own allowable areas and number of stories based on their respective occupancies and type of construction.

BUILDING BELOW HORIZONTAL SEPARATION—THE PODIUM

The building below the horizontal separation is typically referred to as a *podium* or a *pedestal*. In addition to the minimum 3-h fire rating of the floor above it, the other two requirements of the podium are: (a) its type of construction be Type I(A)—the most fire-resistive construction—and (b) it should be fully sprinklered. The occupancies permitted in the podium structure and in above-podium structure are shown in Figure 15.39.

The 2015 IBC places no restrictions on the number of stories of the podium structure—above or below the grade plane—as long as the total height above the grade plane for the entire building (including the podium) does not exceed what is permissible for (the type of construction and occupancy of) the structure above the podium. The number of stories of

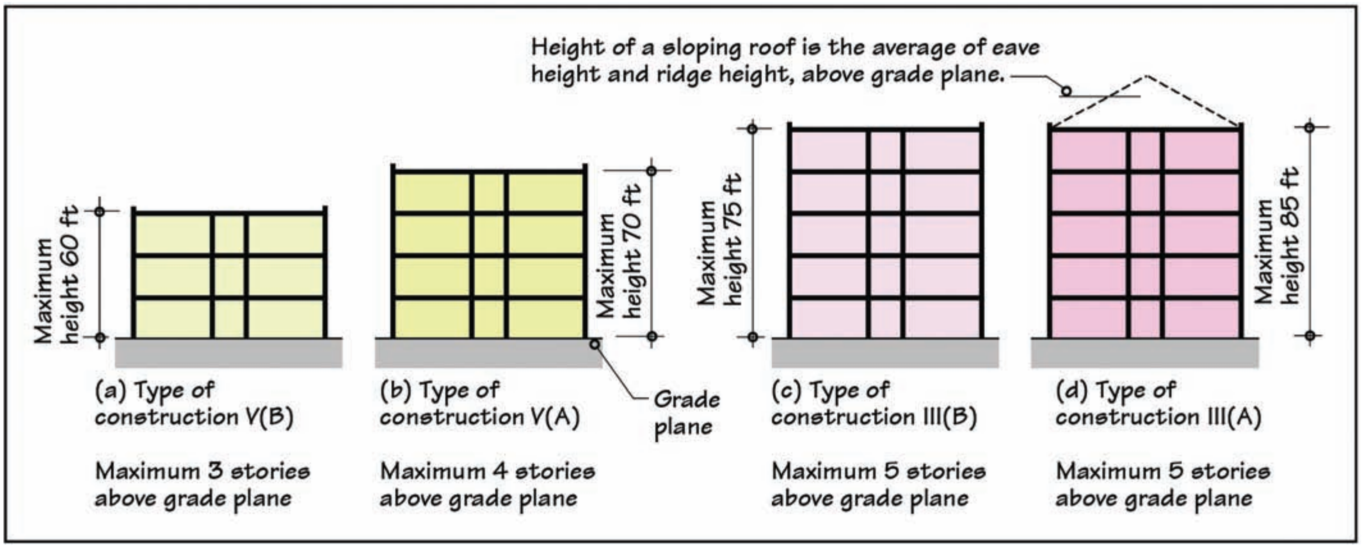

Height of a sloping roof is the average of eave height and ridge height, above grade plane.
Maximum height 60 ft
Maximum height 70 ft
Maximum height 75 ft
Maximum height 85 ft
Grade plane
(a) Type of construction V(B)
Maximum 3 stories above grade plane
(b) Type of construction V(A)
Maximum 4 stories above grade plane
(c) Type of construction III(B)
Maximum 5 stories above grade plane
(d) Type of construction III(A)
Maximum 5 stories above grade plane

FIGURE 15.38 Maximum permissible heights and number of stories for fully sprinklered R-2 occupancy buildings with different types of construction (in wood light frame). The grade plane is the average of finished ground level adjoining the building's exterior walls. (Illustrations not to scale.)

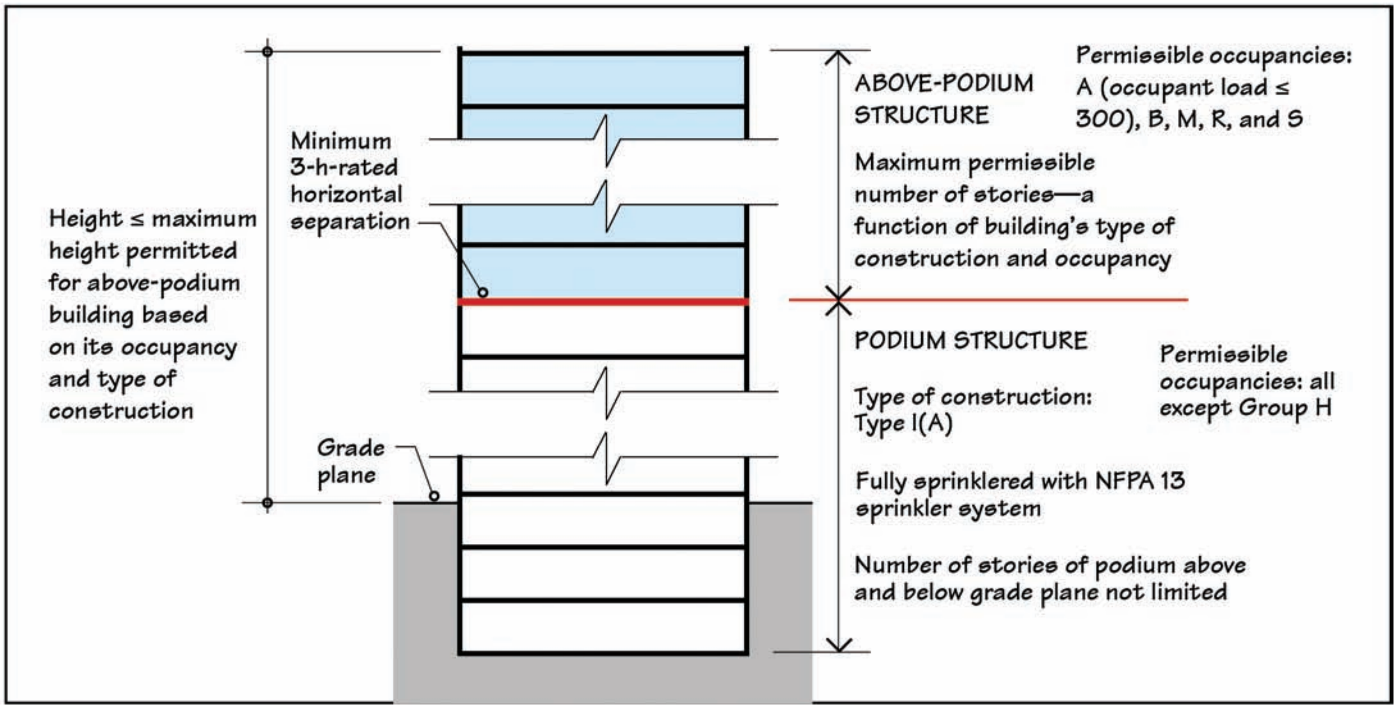

Permissible occupancies: A (occupant load ≤ 300), B, M, R, and S
ABOVE-PODIUM STRUCTURE
Maximum permissible number of stories—a function of building's type of construction and occupancy
Minimum 3-h-rated horizontal separation
Height ≤ maximum height permitted for above-podium building based on its occupancy and type of construction
PODIUM STRUCTURE
Permissible occupancies: all except Group H
Type of construction: Type I(A)
Grade plane
Fully sprinklered with NFPA 13 sprinkler system
Number of stories of podium above and below grade plane not limited

FIGURE 15.39 A section through a podium-type building, showing its essential features and requirements.

the above-podium structure must also meet the requirements of its type of construction and occupancy, see Figure 15.39. The podium and the structure above the podium are together referred to as the *podium-type* or *pedestal-type building*.

WOOD LIGHT-FRAME STRUCTURE ABOVE A PODIUM

A WLF structure supported on a podium results in a taller building and an increase in building area. For example as shown in Figure 15.38(b), the maximum permissible number of stories for a fully sprinklered Type V(A) building (Occupancy R-2) is four with maximum permissible height of 70 ft. If such a building sits atop a podium, it is still allowed the same maximum four stories, but the total number of stories for the entire podium-type building are greater because of the contribution of the podium. However, the total maximum permissible height of the entire building above the grade plane, including the podium, remains unchanged at 70 ft, Figure 15.40(a).

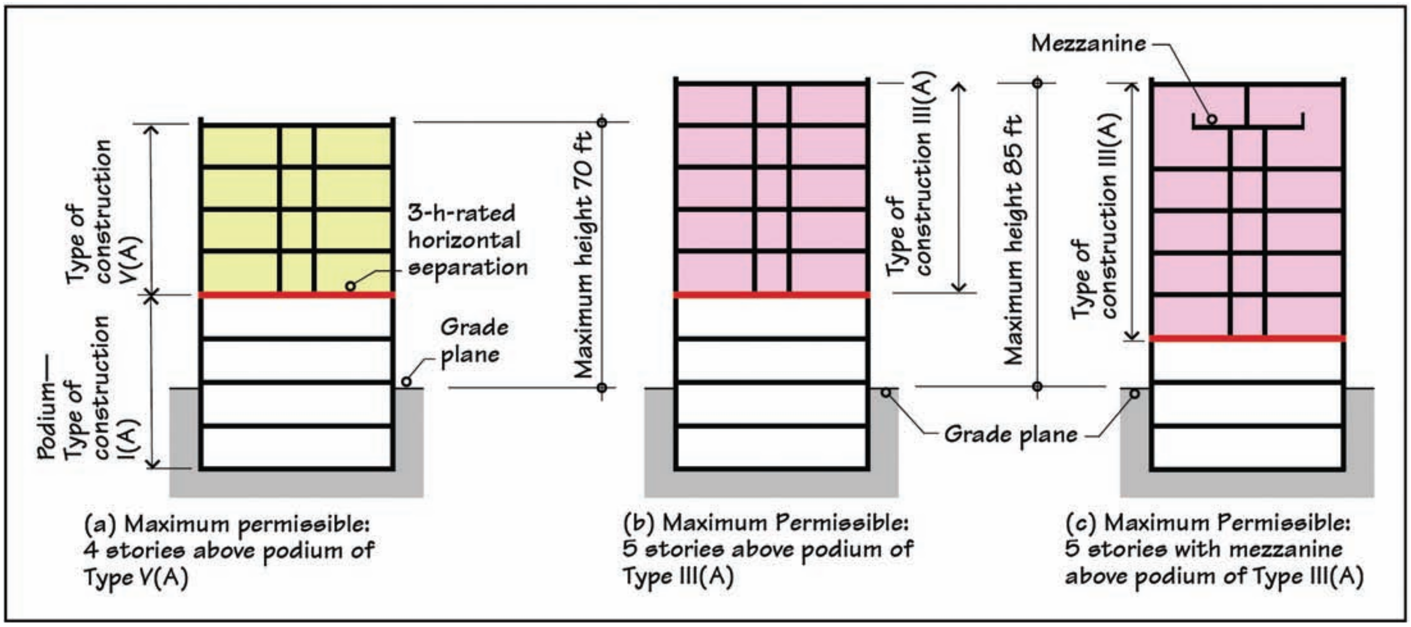

Type of construction V(A)
Podium—Type of construction I(A)
3-h-rated horizontal separation
Grade plane
Maximum height 70 ft
Type of construction III(A)
Maximum height 85 ft
Mezzanine
Type of construction III(A)
Grade plane
(a) Maximum permissible: 4 stories above podium of Type V(A)
(b) Maximum Permissible: 5 stories above podium of Type III(A)
(c) Maximum Permissible: 5 stories with mezzanine above podium of Type III(A)

FIGURE 15.40 Sections through commonly used podium-type buildings. (a) Four stories of Type V(A) building above podium. (b) Five stories of Type III(A) building above podium. (c) Five stories plus mezzanine of Type III(A) building above podium, effectively giving a six-story WLF building.

Note 1: A mezzanine floor does not count toward the number of stories.

Note 2: The number of stories in the podium building above and below the grade plane are not limited by the code as long as the total height of the entire building meets the maximum height limitations given here.

If the type of construction of the same (Occupancy R-2) building is Type III(A), the maximum permissible number of stories for such a building, as shown in Figure 15.38(d), is five with maximum permissible height of 85 ft. Therefore, if this structure sits atop a podium, the total maximum permissible height above grade plane of the entire building, including the podium, is 85 ft, Figure 15.40(b). Because a mezzanine is not counted as a separate story, Type III(A) structure becomes taller with a corresponding decrease in the height of the podium, Figure 15.40(c).

BENEFITS OF CONCRETE PODIUM PLUS WOOD LIGHT-FRAME STRUCTURE

As long as the podium meets the requirements of Type I(A) construction, it can be constructed of any (noncombustible) material—steel or reinforced concrete. However, the use of reinforced concrete is far more common. Because of the light weight of wood, it is possible to support the entire above-podium WLF structure on a thick reinforced concrete podium slab (generally a flat plate slab). It is more difficult to achieve the same result with a concrete-topped steel deck supported on structural steel frame.

The above-podium, WLF structure is permitted to house various occupancies, as shown in Figure 15.39. However, it is most commonly used for multifamily housing (R-2 occupancy). The podium generally houses amenity occupancies, such as retail outlets (Occupancy M), leasing and administrative offices (Occupancy B), restaurants (Occupancy B), parking garage (Occupancy S-2), and so on.

Because WLF yields cost-effective and sustainable structures with associated ease and speed of construction, and the podium provides an increase in building area and height, a podium-type building has become quite popular in recent times. Its use for midrise, multifamily, in-fill housing is helping to regenerate urban areas, curbing urban sprawl. They also cater to the needs of the millennial generation, who desiring greater career mobility do not wish to be burdened with single-family homes and long commute times from far-flung suburbs. Figure 15.41 shows a bird's-eye view of a typical podium-type building under construction in an urban setting and Figures 15.42 and 15.43 show some of its details. Figure 15.44 shows the same building after completion.

SHORTENING IN HEIGHT OF WLF STRUCTURES

While there are several advantages of WLF construction previously mentioned, one of its major disadvantages is shortening in the height of the structure during construction and

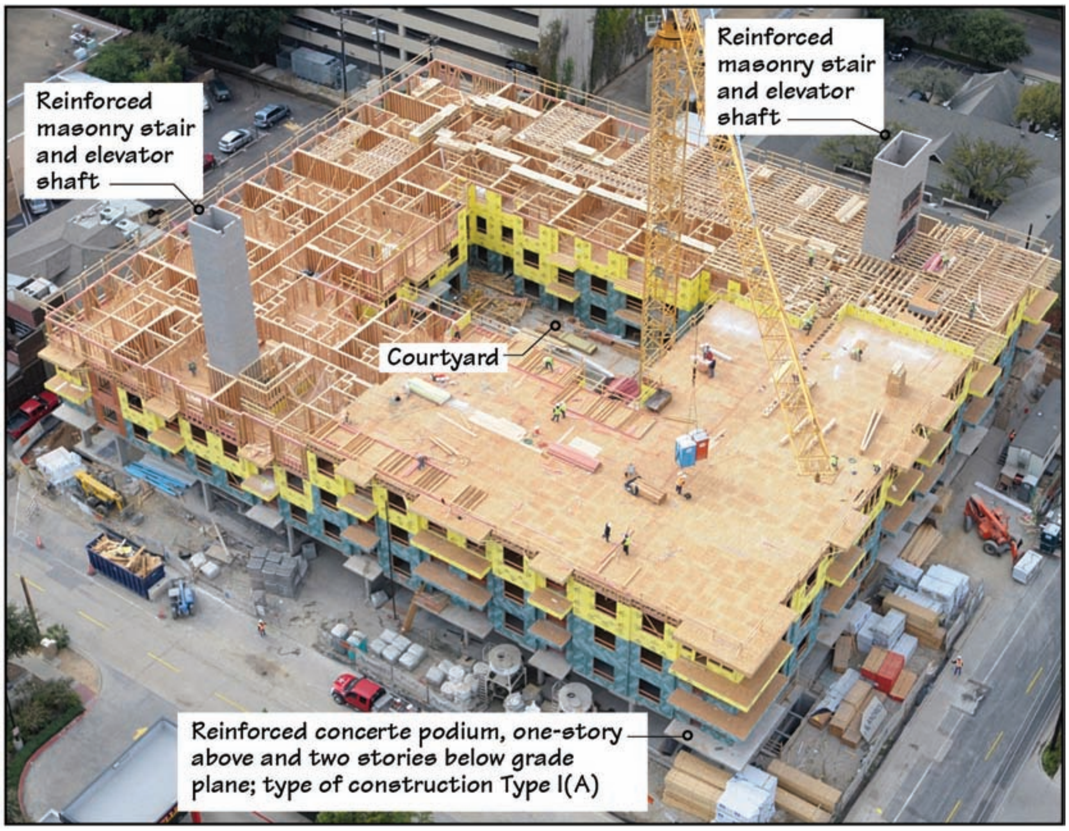

Reinforced masonry stair and elevator shaft
Reinforced masonry stair and elevator shaft
Courtyard
Reinforced concerte podium, one-story above and two stories below grade plane; type of construction Type I(A)

FIGURE 15.41 A building with five-story wood frame on a reinforced concrete podium under construction in Dallas, Texas. (Photo courtesy of Hull Associates, Arlington, Texas)

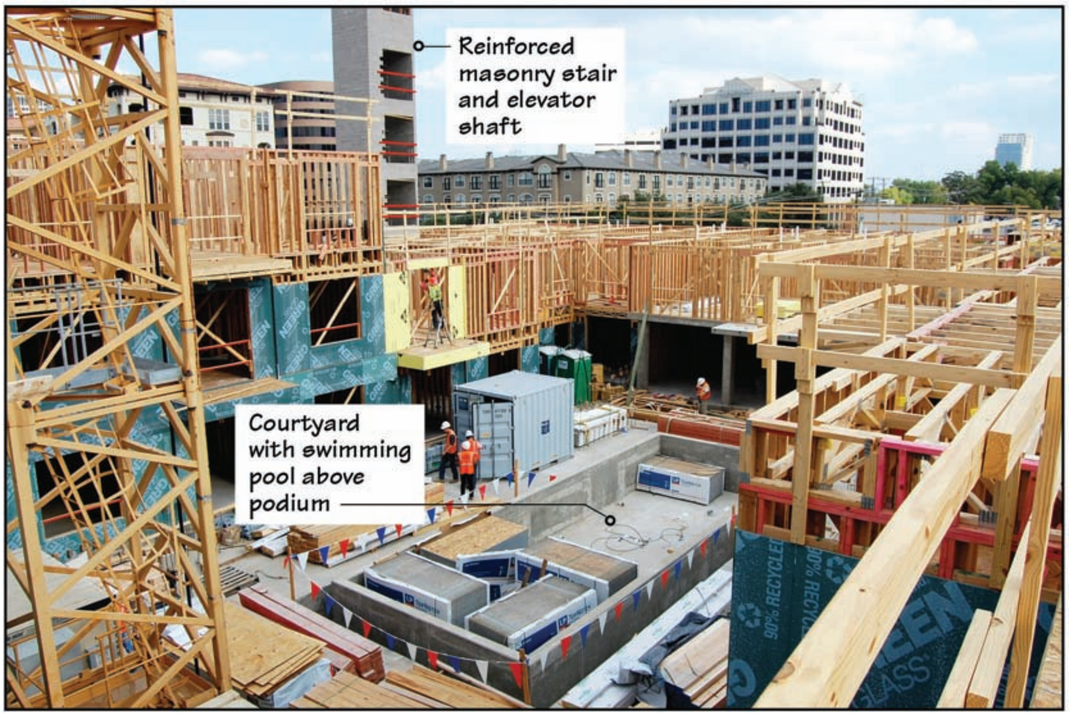

Reinforced masonry stair and elevator shaft
Courtyard with swimming pool above podium

FIGURE 15.42 A view into the courtyard of the building of Figure 15.41 under construction, showing the swimming pool area above the podium.

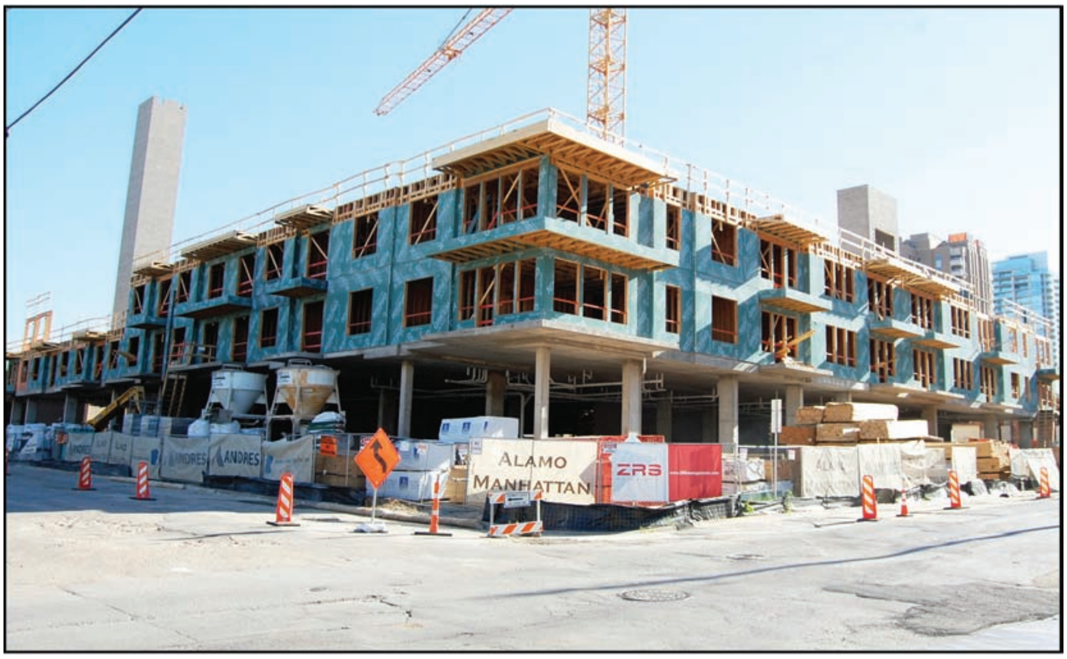


FIGURE 15.43 A street view of the podium-type building of Figure 15.41 under construction.

after completion. This requires careful detailing of structural and nonstructural elements constructed of different materials that connect with WLF structure and possess different dimensional behavior. Examples of such elements are reinforced concrete or reinforced masonry stair and elevator shafts, HVAC shafts, utility pipes (plumbing, electrical, communication, and fuel), etc.

The shortening in the height of WLF structure is caused by: (a) shrinkage of wood, (b) creep in wood, and (c) settlement under construction gaps between studs and the top and bottom plates. The settlement occurs because it is impossible to have all studs exactly the same height (some are slightly shorter than others) and all are not absolutely square cut. Under sustained load, the gaps close and the structure settles down. Shrinkage and creep add to the settlement effect. 2015 IBC Section 2304 mandates that for a wood structure taller than two stories, an analysis of structural shortening be presented to illustrate that it will not adversely affect the building.

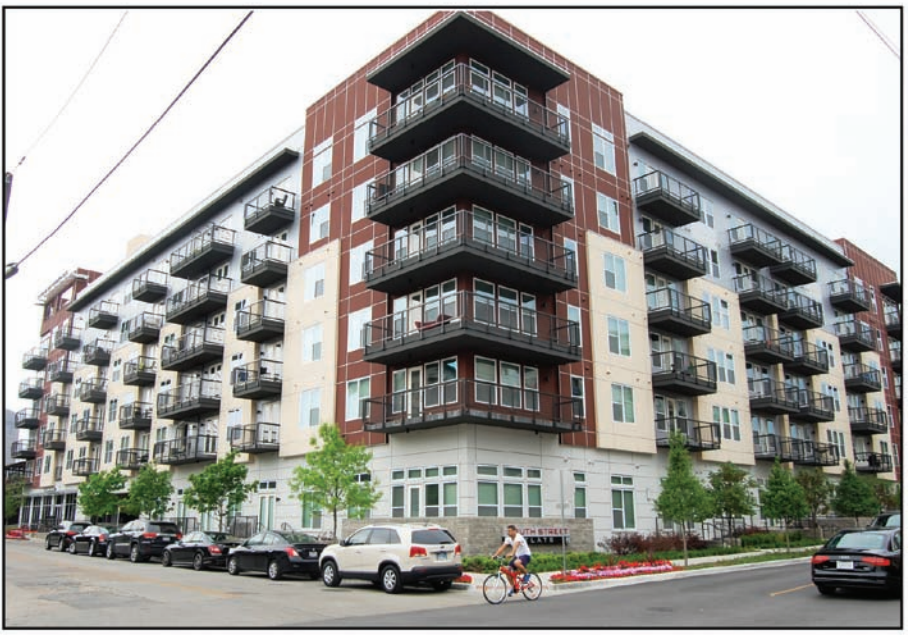


FIGURE 15.44 A street view of the completed podium-type building of Figure 15.41.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

27. Because a ridge board is a structural member, its size depends on roof loads.
- **a.** True **b.** False

28. A bird's mouth cut in rafters is made at the ridge.
- **a.** True **b.** False

29. In a roof with a ridge beam,
- **a.** ceiling joists are spaced at 12 in. on center maximum.
- **b.** ceiling joists are spaced at 16 in. on center maximum.
- **c.** ceiling joists are spaced at 24 in. on center maximum.
- **d.** none of the above.

30. The most commonly used material for floor sheathing in a wood light-frame building is
- **a.** 1 × 4 lumber.
- **b.** OSB panels.
- **c.** high-density fiber board panels.
- **d.** high-density fiber board panels laminated to gypsum board.
- **e.** gypsum board panels.

31. Metal clips used to connect roof sheathing panels are generally
- **a.** H-shaped. **b.** U-shaped.
- **c.** V-shaped. **d.** either U- or V-shaped.

32. If the cross-grain lumber dimensions in a WLF building are the same throughout the entire building, it is not subjected to any swelling or shrinkage.
- **a.** True **b.** False

33. The type of construction that can be achieved with wood light-frame members is
- **a.** Type I(A) or Type 1(B). **b.** Type II(A) or Type II(B).
- **c.** Type III(A) or Type III(B). **d.** Type V(A) or Type V(B).
- **e.** Type III(A), III(B), V(A), or V(B).

34. The maximum number of stories allowed by the International Building Code for a fully sprinklered, R-2 occupancy building in Type V(B) construction is
- **a.** five. **b.** four.
- **c.** three. **d.** two.

35. In a podium-type building, the horizontal separation assembly must have a minimum fire rating of
- **a.** 4 h. **b.** 3 h.
- **c.** 2 h. **d.** 1 h.
- **e.** none of the above.

36. The structure below the podium in a podium-type building must be fully sprinklered only if used for automobile parking.
- **a.** True **b.** False

37. The podium structure in a podium-type building must be Type I(A) construction.
- **a.** True **b.** False

PRINCIPLES IN PRACTICE

Constructing a Two-Story Wood Light-Frame Building

The following text and illustrations show the process and sequence of construction of a two-story wood light-frame (WLF) building. Some builders may follow a slightly different process or sequence.

Several foundation systems can be used in WLF construction, depending on the soil conditions and climate (Chapter 12). In this example, a concrete slab-on-ground (also called *slab-on-grade*) foundation has been used.

STEP 1: FOUNDATION PREPARATION

If the foundation for a WLF building consists of a slab-on-grade, as shown in Figure 1, the ground must first be prepared to receive the slab. This includes clearing the site of vegetation and undesirable topsoil and grading the site to provide appropriate

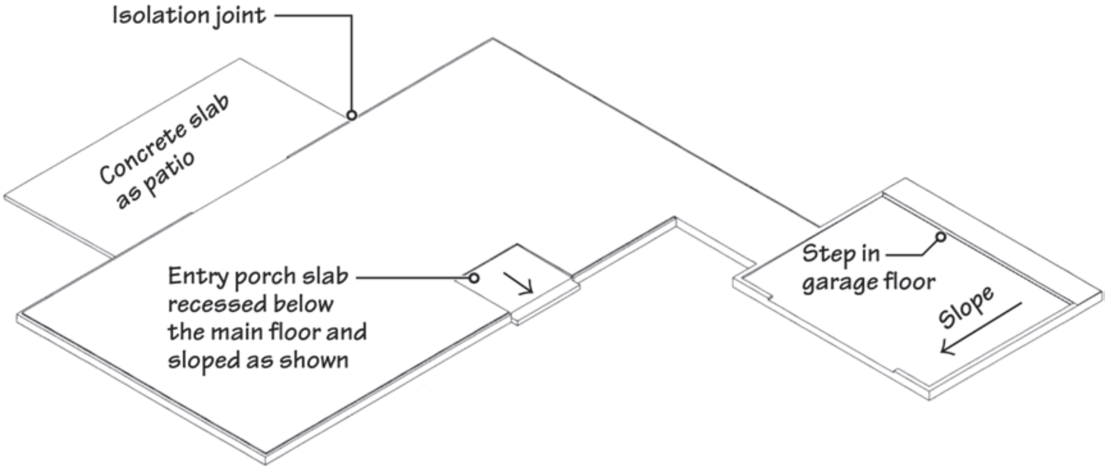

Isolation joint
Concrete slab as patio
Entry porch slab recessed below the main floor and sloped as shown
Step in garage floor
Slope

FIGURE 1 Diagram of a concrete slab-on-grade (also called a *concrete slab-on-ground*) foundation.

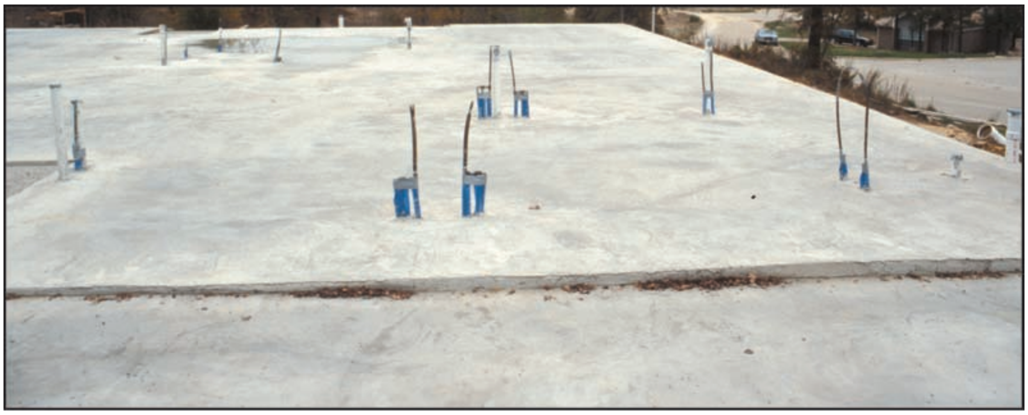


FIGURE 2 A typical completed slab-on-grade ready to receive the WLF superstructure. Note that the utilities extend above the slab (referred to as *stubbed out* of the slab).

drainage. Trenches are then dug for grade beams as required, as well as underground utilities (sewage, wastewater, water supply, natural gas pipes, and electrical and telecommunication lines). Trenches are backfilled after the utilities are laid and then compacted. Finally, the slab is constructed, as shown in Figure 2 (see also Sections 22.11 and 22.12).

STEP 2: FRAMING THE FIRST-FLOOR WALLS

Before the wall framing for the ground floor begins, chalk lines are placed (snapped) on the slab to locate the walls per the architectural floor plan, Figures 3 and 4.

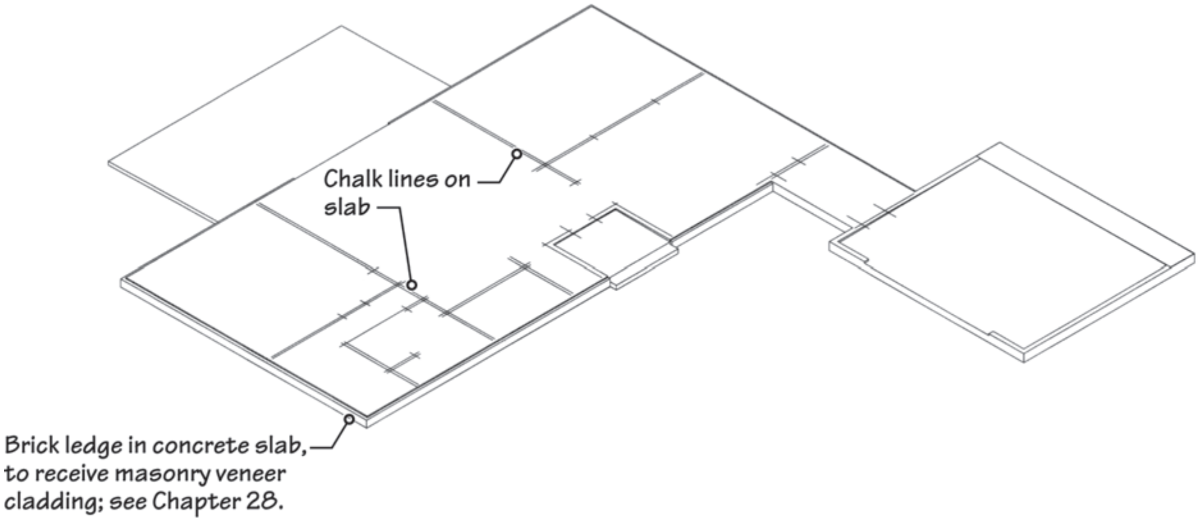

Chalk lines on slab
Brick ledge in concrete slab, to receive masonry veneer cladding; see Chapter 28.

FIGURE 3 Slab-on-grade with chalk lines.

(Continued)

Constructing a Two-Story Wood Light-Frame Building (*Continued*)

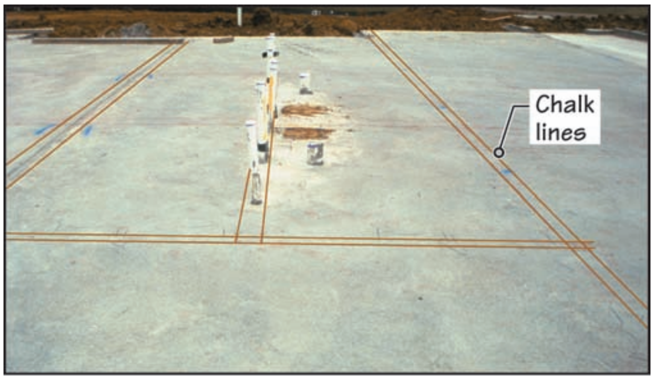

Chalk lines

FIGURE 4 Chalk lines on the slab indicate the location of the walls. Note that plumbing pipes align and are located within the thickness of the wall.

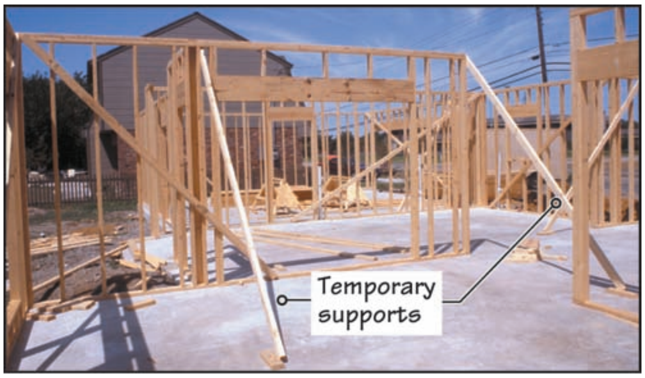

Temporary supports

FIGURE 5 Wall assembly under construction.

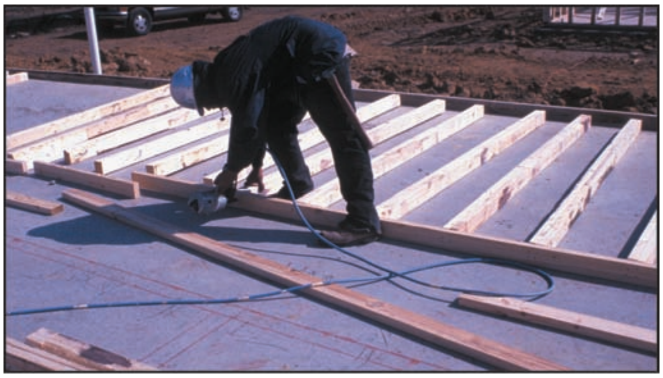


FIGURE 6 Walls are typically framed on the slab or floor platform and subsequently tilted up into position.

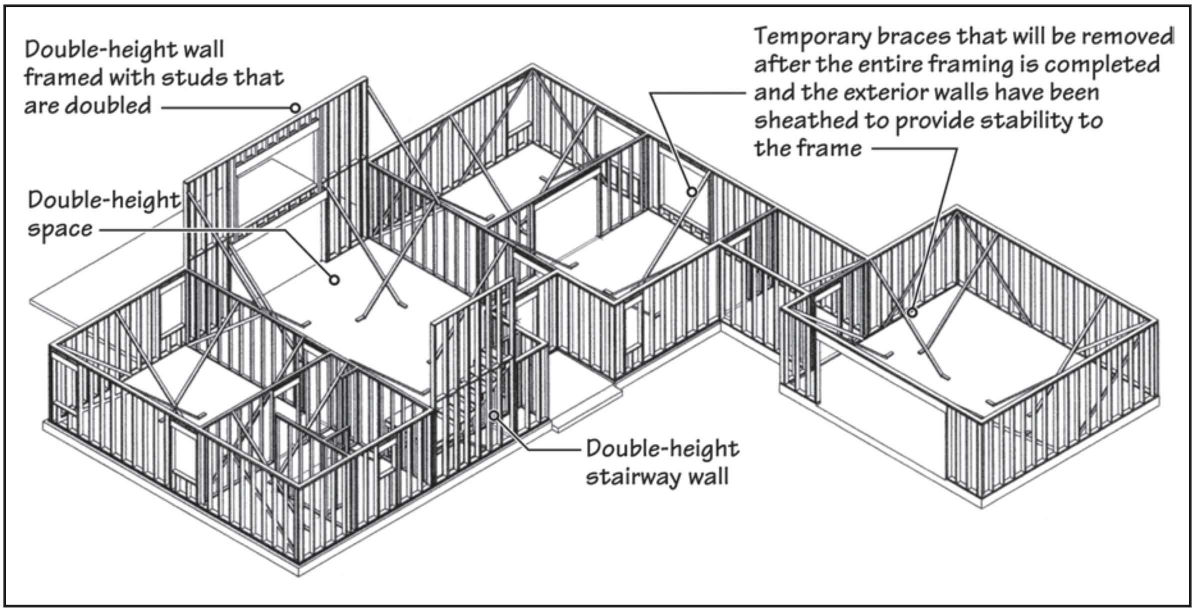

Double-height wall framed with studs that are doubled
Double-height space
Temporary braces that will be removed after the entire framing is completed and the exterior walls have been sheathed to provide stability to the frame
Double-height stairway wall

FIGURE 7 Ground-floor wall framing is completed.

With the chalk lines in place, framing the ground floor walls can begin, Figures 5 to 7. Temporary braces stabilize the walls until the frame is complete and the exterior walls are sheathed. When double-height spaces are required, continuous or double studs are used to frame the high segments of the wall.

STEP 3: FRAMING THE SECOND FLOOR

Upon completion of the first-floor walls, joists can be installed for the second-story floor, Figures 8 and 9. Unless the plan dictates otherwise, the floor joists are oriented to span the short direction. At locations such as stair openings or step-down floors, floor joists may be doubled or tripled, or a beam may be used to carry the greater load.

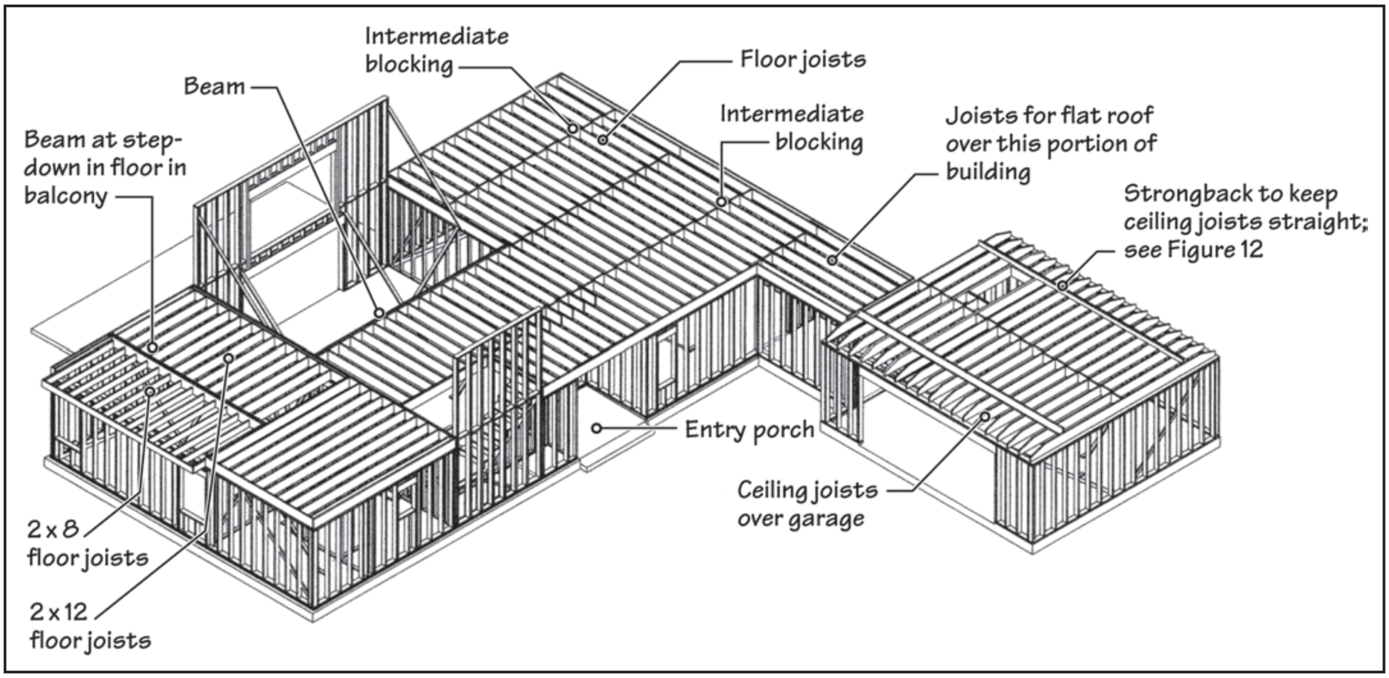

Intermediate blocking
Floor joists
Beam
Beam at step-down in floor in balcony
Intermediate blocking
Joists for flat roof over this portion of building
Strongback to keep ceiling joists straight; see Figure 12
Entry porch
Ceiling joists over garage
2 x 8 floor joists
2 x 12 floor joists

FIGURE 8 Floor framing at the second floor.

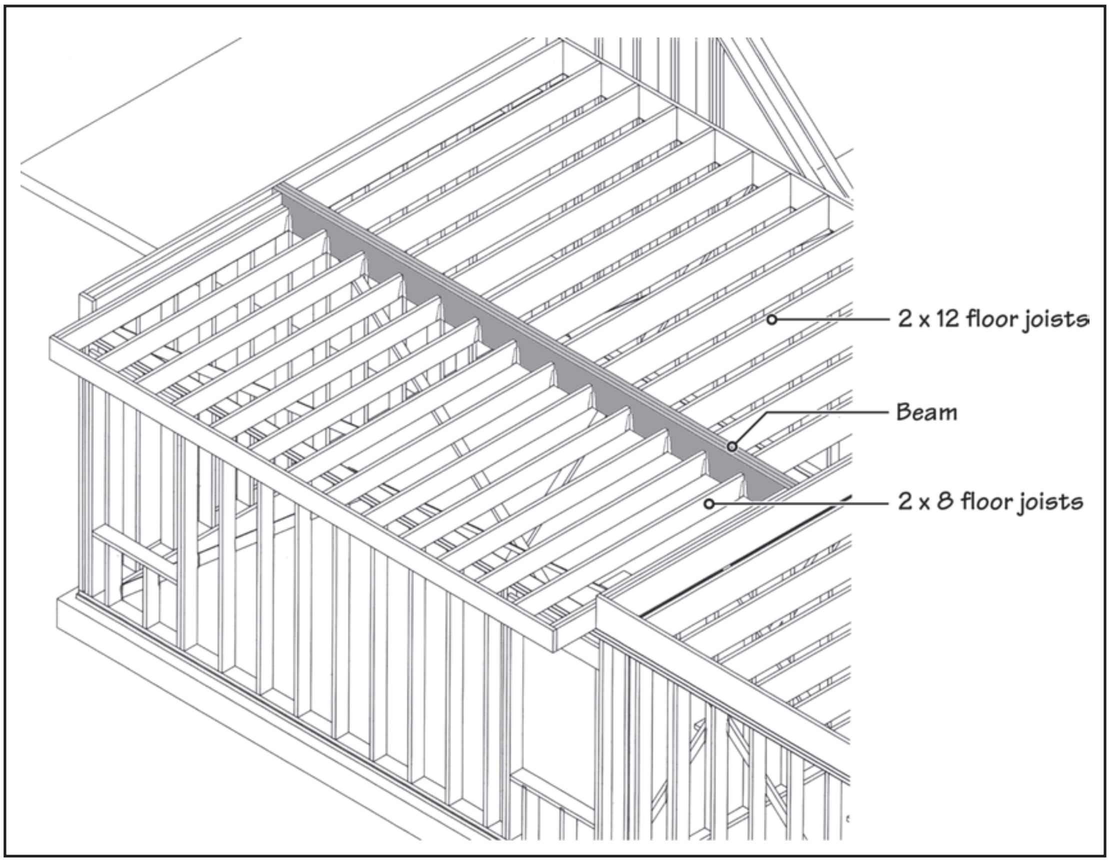

2 x 12 floor joists
Beam
2 x 8 floor joists

FIGURE 9 Detail of the floor framing at a step down in the floor (see Figure 8). Note that 2 × 12 floor joists are tripled to form a built-up beam. The 2 × 8 floor joists supported by the beam are cantilevered beyond the supporting wall below. This is similar to the example in Figures 15.17 and 15.18.

STEP 4: FLOOR SHEATHING AT THE SECOND FLOOR

Next, the sheathing is applied to the floor joists to form the second-story floor assembly, Figure 10.

(Continued)

PRINCIPLES IN PRACTICE

Constructing a Two-Story Wood Light-Frame Building (*Continued*)

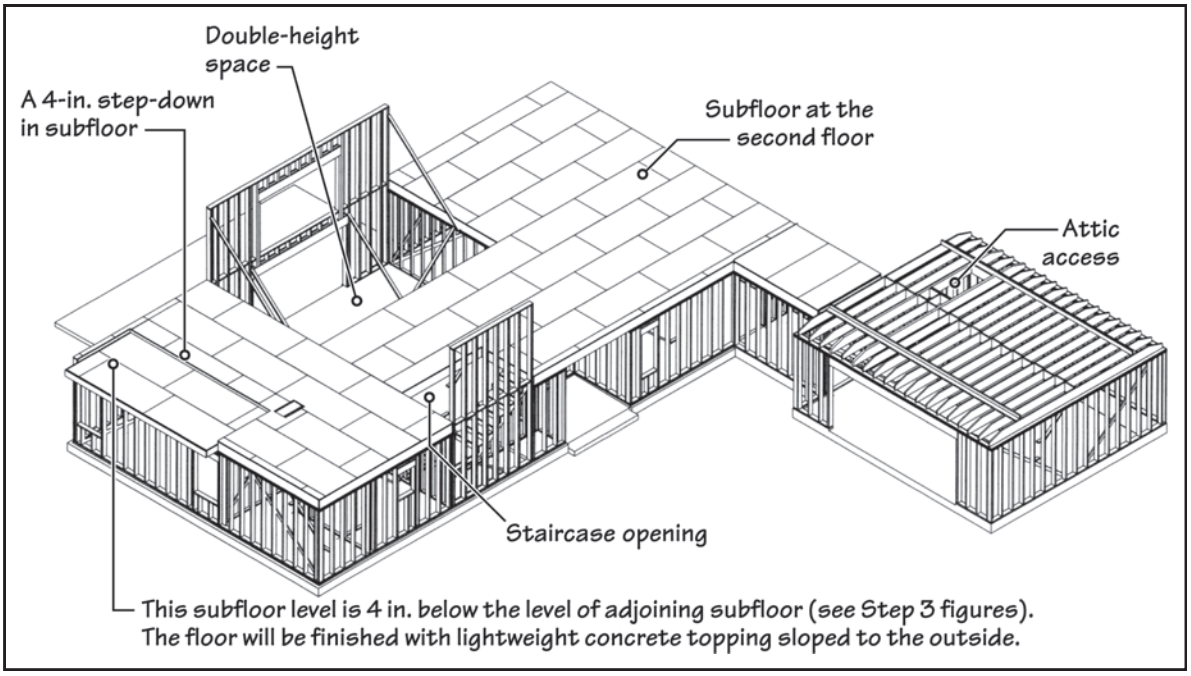

Double-height space
A 4-in. step-down in subfloor
Subfloor at the second floor
Attic access
Staircase opening
This subfloor level is 4 in. below the level of adjoining subfloor (see Step 3 figures). The floor will be finished with lightweight concrete topping sloped to the outside.

FIGURE 10 The plywood and OSB sheathing are staggered, glued, and nailed to the floor joists.

STEP 5: SECOND-FLOOR WALL FRAMING

The walls for the second story are constructed on the subfloor surface, Figure 11, in a manner similar to that shown in Step 2.

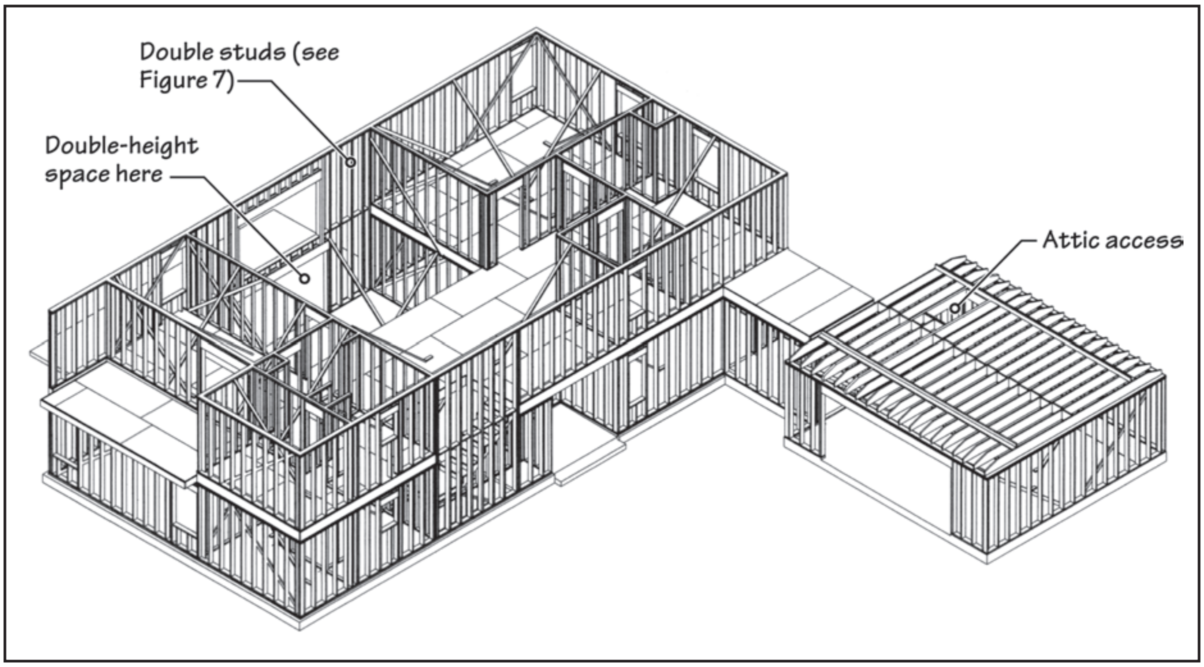

Double studs (see Figure 7)
Double-height space here
Attic access

FIGURE 11 Walls are erected, framed, and braced.

STEP 6: CEILING JOIST AND ROOF FRAMING

In a stick-framed roof, ceiling joists span across the walls, Figure 12. Rafters are then set in place to complete the roof framing. When roof trusses are used, they replace the function of ceiling joists and rafters in one unit.

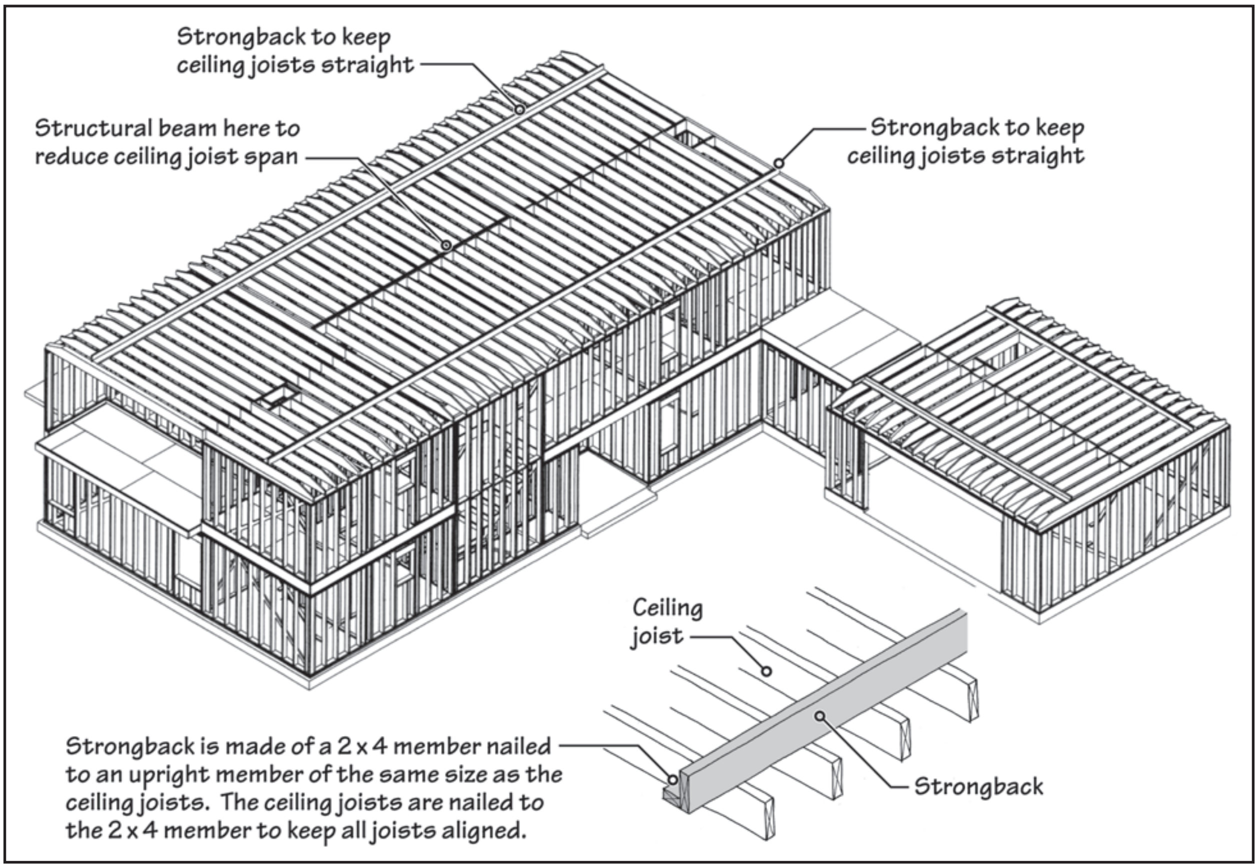

Strongback to keep ceiling joists straight
Structural beam here to reduce ceiling joist span
Strongback to keep ceiling joists straight
Ceiling joist
Strongback is made of a 2 x 4 member nailed to an upright member of the same size as the ceiling joists. The ceiling joists are nailed to the 2 x 4 member to keep all joists aligned.
Strongback

FIGURE 12 Ceiling-joist framing. Note the use of strongbacks and of the structural beam (resting on two opposite walls) to reduce the ceiling-joist span.

STEP 7: WALL AND ROOF SHEATHING

With the framing complete, Figure 13, the building is ready to receive wall sheathing, Figure 14, and then roof sheathing, Figure 15, which greatly enhances the structural rigidity. Note that some framers may apply wall sheathing prior to roof framing. After the walls and roof have been sheathed, the structural frame is stable. Temporary interior wall supports can now be removed, allowing work on interior finishes.

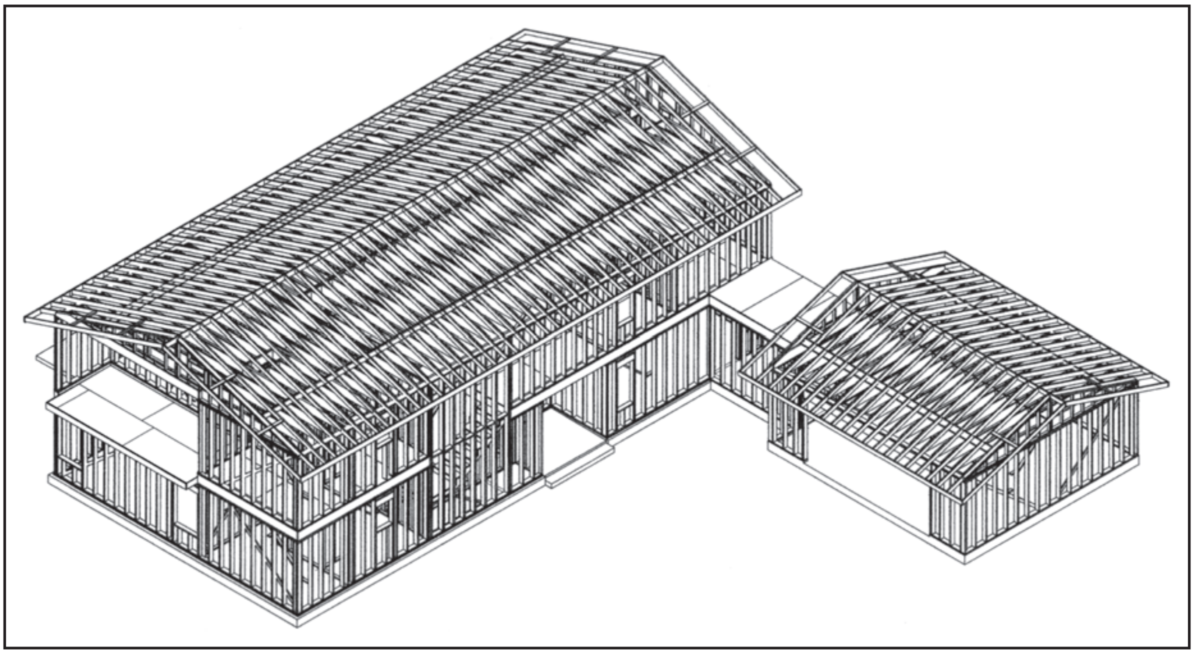


FIGURE 13 Roof framing is completed. Note the conditions at the gable end and eave overhangs.

(Continued)

Constructing a Two-Story Wood Light-Frame Building (*Continued*)

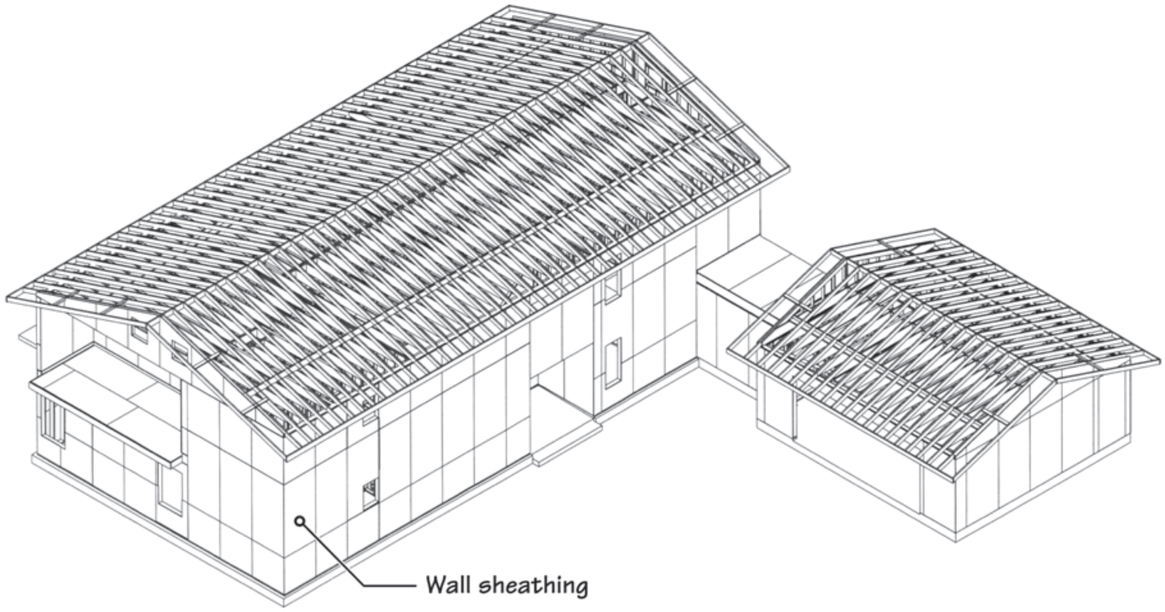


FIGURE 14 Sheathing is installed on all exterior walls.

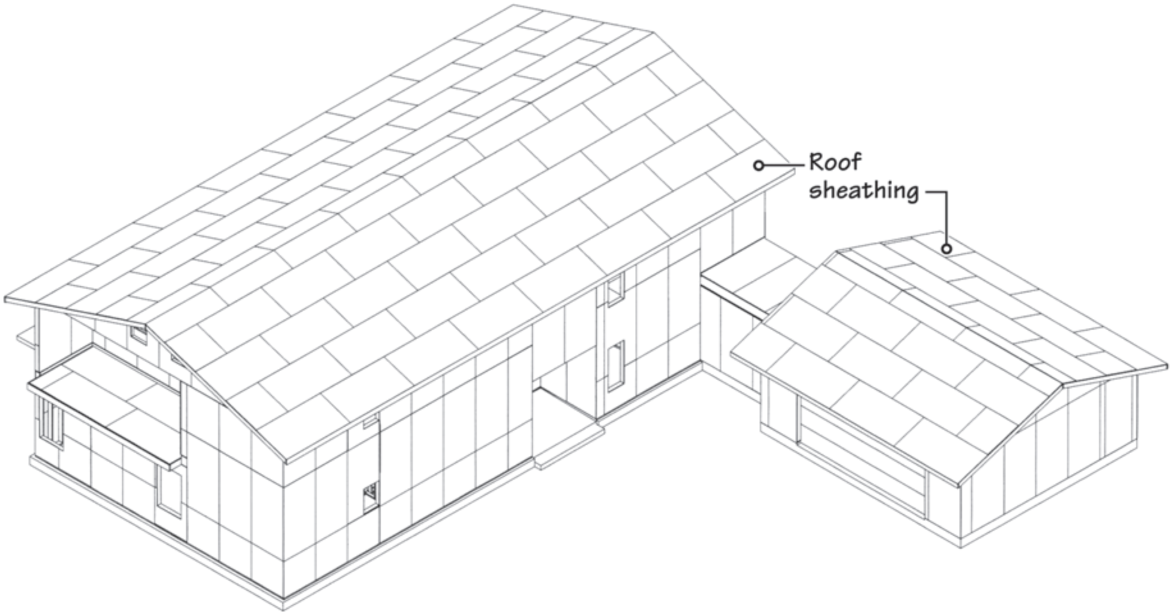


FIGURE 15 Roof sheathing has been installed in a staggered pattern. After the walls and roof have been sheathed, the structural frame is stable. Temporary interior wall supports can now be removed, allowing work on interior finishes.

STEP 8: EXTERIOR AND INTERIOR FINISHES

Roofing, including underlayment, Figure 16, and finish cover, Figure 17 (discussed in Chapter 34) are generally applied first to dry-in the interior spaces and allow inside work to progress. Interior work, including rough plumbing and electrical and wall insulation, is completed before drywall and interior finishes. Exterior work includes windows and doors, moisture/air retarder, and finish surface treatment, Figure 18.

PRINCIPLES IN PRACTICE

How a WLF Building Resists Loads

All loads on a building, regardless of the type, must terminate in the ground, where they are finally absorbed. In other words, the ground serves as an infinitely large sink for all loads. In proceeding from its point of origin in the building down to the ground, a load will generally traverse through several intermediate components.

The path that a particular load takes through various components helps us understand the role of each component in resisting the loads. Additionally, it helps to determine the magnitude and types of stresses to which each component is subjected. Both gravity and lateral loads must be considered, and the stresses caused by each load are added to determine a component's size.

GRAVITY LOAD PATH

The path of gravity loads through a WLF building is relatively simple to trace and is shown in Figure 1. In tracing the gravity load path, we proceed from the top and work our way down. Rafters transmit roof loads to the supporting walls. As these loads travel down, they meet the load transmitted to the wall from the floor, where they add up. Further down into the wall, the load from the next floor is added. Finally the load reaches the foundation.

Observe that the load on the wall increases as it proceeds toward the foundation. This implies that the wall should be made stronger at each lower floor. For the sake of simplicity, however, wall strength at upper floors may be kept the same as that on the lowest floor. For instance, if the first-floor walls are required to consist of 2 × 6 studs at 16 in. on center, the same stud size and spacing can also be used in the upper floors.

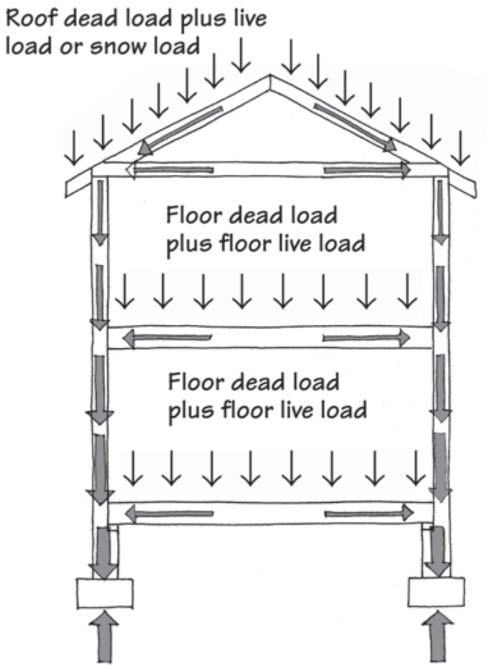
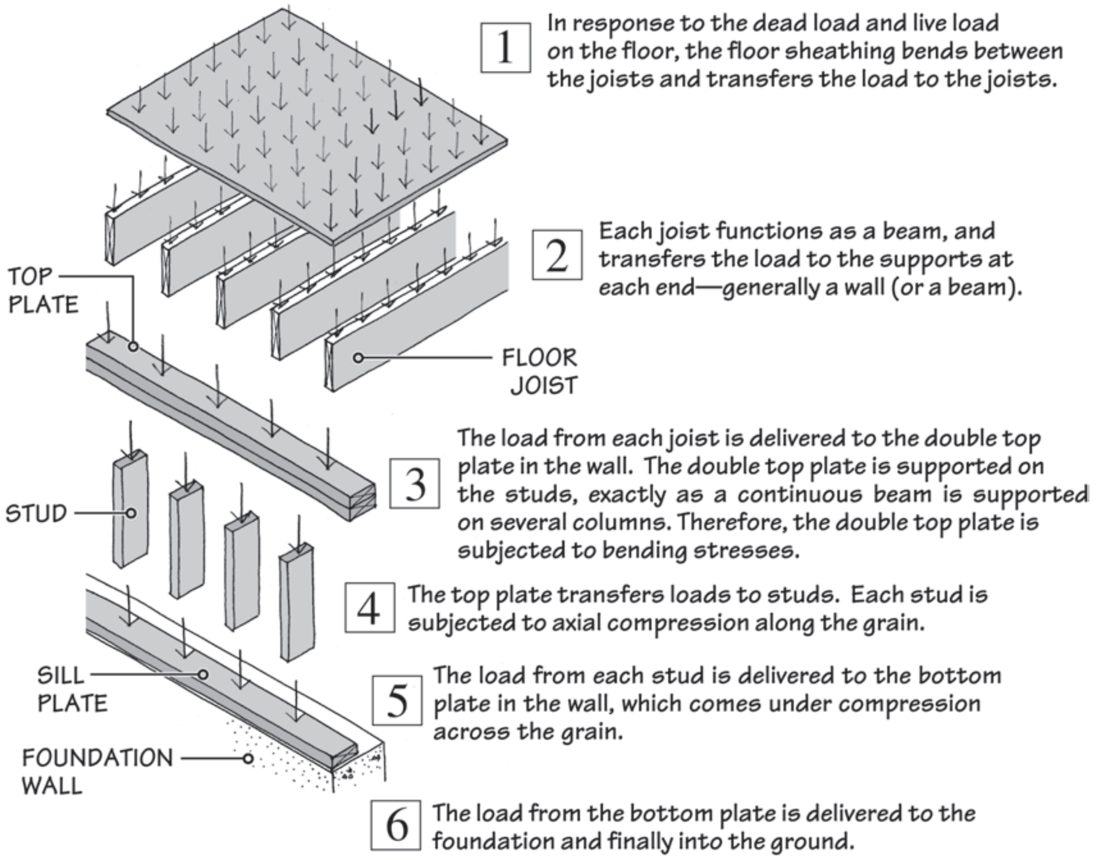

Roof dead load plus live load or snow load
Floor dead load plus floor live load
Floor dead load plus floor live load

FIGURE 1 Journey of gravity loads through a WLF building.

The load paths shown in Figure 1 indicate that a load-bearing wall at an upper floor must be aligned with that at the lower floor. Although a small offset in load-bearing walls can be managed structurally, it is advisable to plan for vertical alignment of all load-bearing walls. Figure 2 shows the details of how the gravity loads acting on an intermediate floor are transmitted to the foundation.



1 In response to the dead load and live load on the floor, the floor sheathing bends between the joists and transfers the load to the joists.

2 Each joist functions as a beam, and transfers the load to the supports at each end—generally a wall (or a beam).

3 The load from each joist is delivered to the double top plate in the wall. The double top plate is supported on the studs, exactly as a continuous beam is supported on several columns. Therefore, the double top plate is subjected to bending stresses.

4 The top plate transfers loads to studs. Each stud is subjected to axial compression along the grain.

5 The load from each stud is delivered to the bottom plate in the wall, which comes under compression across the grain.

6 The load from the bottom plate is delivered to the foundation and finally into the ground.

FIGURE 2 Details of the path of gravity loads acting on an intermediate floor of a WLF building.

(Continued)

How a WLF Building Resists Loads (*Continued*)

LATERAL LOAD PATH

In tracing the lateral loads through the structure, let us consider the loads acting on one of the walls (say, the gable-end wall) of a two-story WLF building, Figure 3. In resisting these loads, the wall behaves as a vertical slab supported by three elements—the foundation at the bottom, the intermediate floor, and the roof-ceiling assembly. The loads transmitted to each of these three elements are proportional to their respective tributary areas.

Thus, if the floor-to-floor height and the floor-to-roof height are each 10 ft, the lateral loads on the lowest 5 ft of the wall are transmitted to the foundation. The loads on the next 10 ft of the wall are transmitted to the (second) floor, whereas the loads on the remaining (uppermost) portion of the wall are transmitted to the roof.

In a WLF building, the transfer of lateral loads from the wall to the floor or the roof occurs through the studs, which function as vertical beams. Therefore, in high-wind regions, the size and spacing of studs in exterior walls may be dictated by the wind loads. In regions where the wind loads are small, gravity loads dictate the size and spacing of studs.

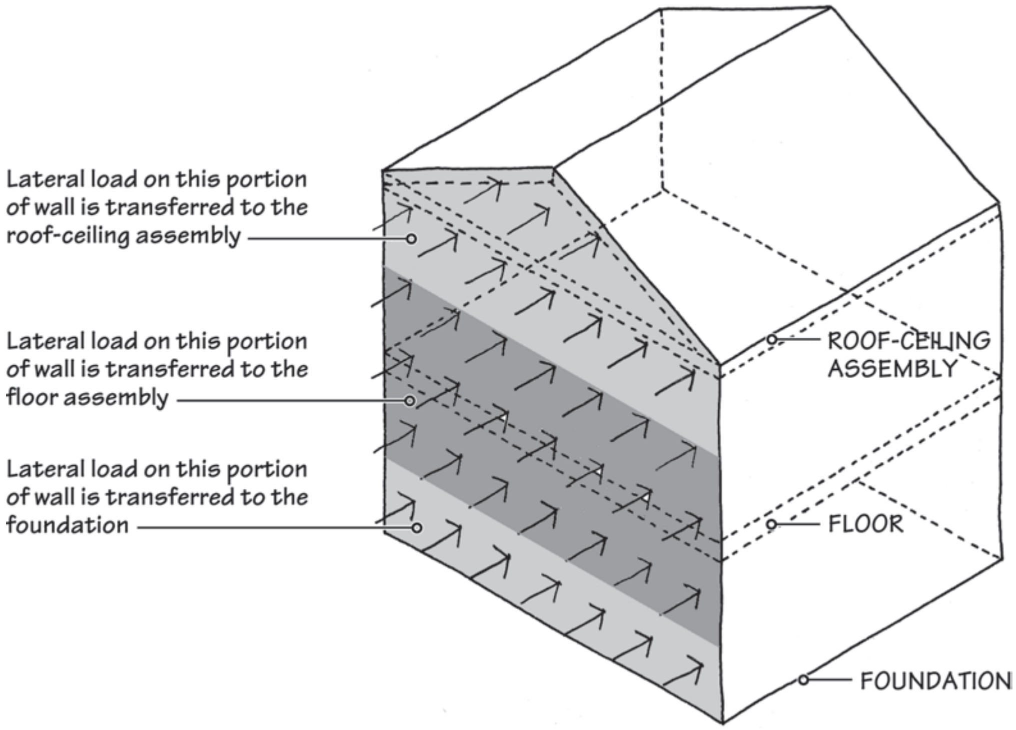

Lateral load on this portion of wall is transferred to the roof-ceiling assembly
Lateral load on this portion of wall is transferred to the floor assembly
Lateral load on this portion of wall is transferred to the foundation
ROOF-CEILING ASSEMBLY
FLOOR
FOUNDATION

FIGURE 3 Journey of lateral loads acting on one of the walls of a WLF building. Note that the lateral loads assumed on the (gable-end) wall are shown as push-in loads, but they could just as well be suction loads.

HORIZONTAL DIAPHRAGMS

The load transmitted from the wall to the foundation is absorbed into the ground, where all loads must eventually reach. Therefore, this load will not be traced any further.

The load transmitted to the (second) floor lies in the plane of the floor, Figure 4. In resisting this load, the floor behaves as a deep beam, with side walls functioning as its supports. One of the characteristics of a deep beam is that the tensile and compressive stresses created in it are concentrated mainly at its extreme edges.

The action of the floor in transferring the lateral loads to its supports (side walls) through deep beam action is called *diaphragm action,* and the tensile and compressive stresses in it are called *diaphragm tension* and *diaphragm compression*, respectively.

In practice, we assume that diaphragm tension and compression are resisted by the double top plate supporting the floor. The presence of diaphragm tension requires that the top plate, as well as the adjacent rim joist, be continuous.

Just as a floor works as a diaphragm in transferring lateral loads to side walls, a roof works in the same way—although as a folded diaphragm.

SHEAR WALLS

The loads acting on a side wall are those that have been transferred to it from the floor and roof diaphragms. In resisting these loads, the wall is supported only at the foundations. Therefore, it behaves as a vertical cantilever carrying in-plane loads. This makes the wall *rack,* or deform angularly, Figure 5.

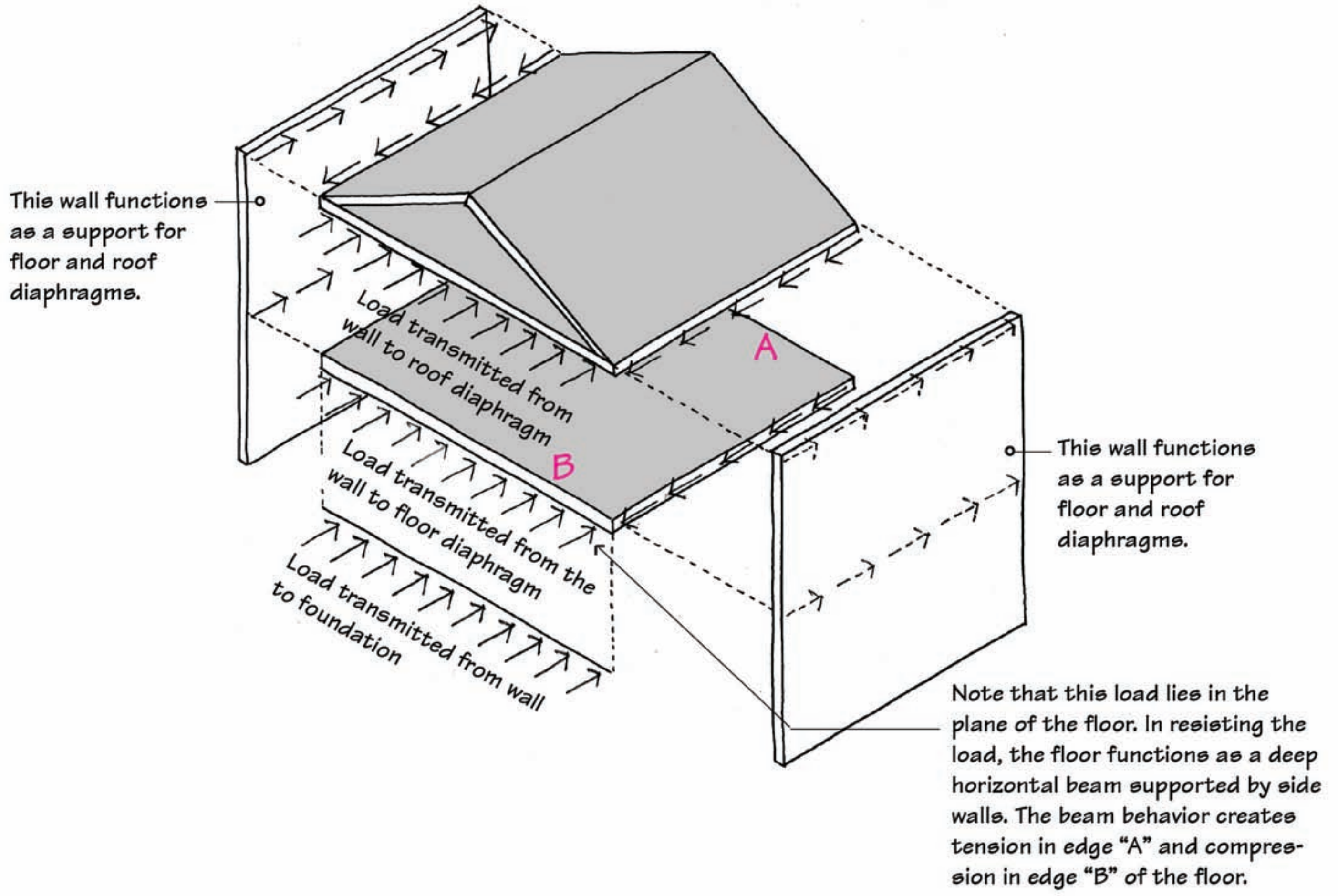
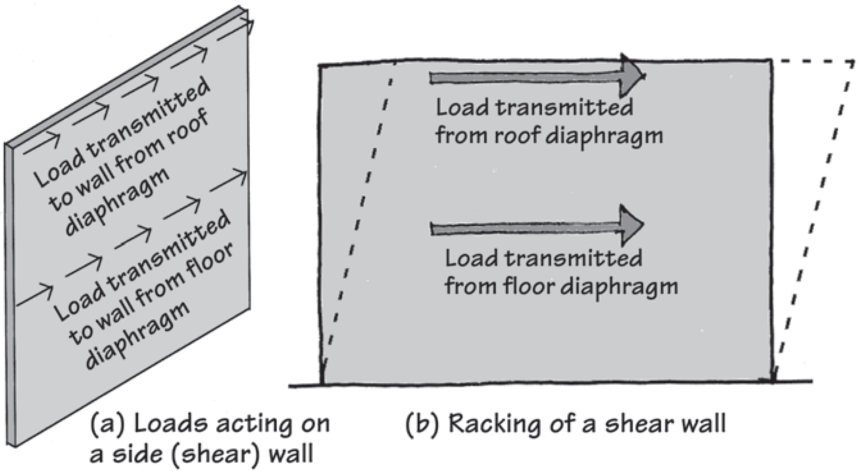

This wall functions as a support for floor and roof diaphragms.
Load transmitted from wall to roof diaphragm
Load transmitted from the wall to floor diaphragm
Load transmitted from wall to foundation
A
B
This wall functions as a support for floor and roof diaphragms.
Note that this load lies in the plane of the floor. In resisting the load, the floor functions as a deep horizontal beam supported by side walls. The beam behavior creates tension in edge "A" and compression in edge "B" of the floor.

FIGURE 4 Load transfer from the (gable-end) wall to floor and roof diaphragms.


Load transmitted to wall from roof diaphragm
Load transmitted to wall from floor diaphragm
Load transmitted from roof diaphragm
Load transmitted from floor diaphragm

(a) Loads acting on a side (shear) wall (b) Racking of a shear wall

FIGURE 5 Racking in a WLF wall due to in-plane loads.

A WLF wall must, therefore, be braced against racking, which is achieved through the use of plywood, OSB sheathing, or diagonal braces (Section 15.10). Because the racking and the consequent angular deformation are caused by shear forces, a wall braced to resist racking is referred to as a *shear wall*. In a rectilinear box-type building with four walls, all walls must be designed as shear walls to account for lateral loads from either one of the two principal directions.

In transferring the loads to the foundation, a shear wall is subjected to sliding, Figure 6(a) and overturning, Figures 6(b) and 6(c). The sliding action in a WLF building is resisted by foundation anchor bolts. The overturning action is also resisted by the same bolts if the overturning force is small. In a high-wind or seismic region, special hold-down bolts are required in each shear wall segment to counteract excessive overturning forces. A typical hold-down bolt is shown in Figure 6(d).

(Continued)

PRINCIPLES IN PRACTICE

How a WLF Building Resists Loads (*Continued*)

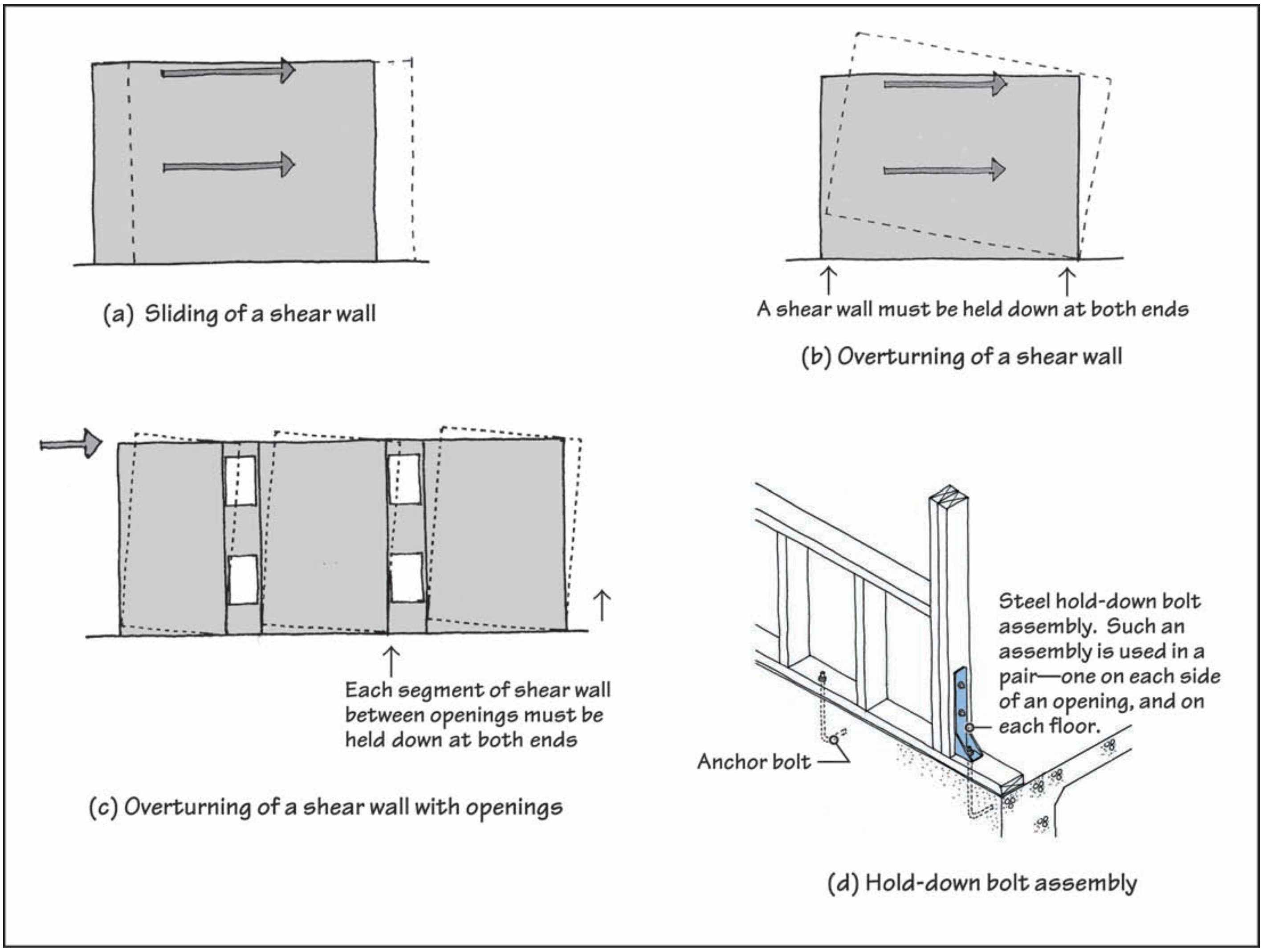

(a) Sliding of a shear wall
A shear wall must be held down at both ends
(b) Overturning of a shear wall
Each segment of shear wall between openings must be held down at both ends
(c) Overturning of a shear wall with openings
Steel hold-down bolt assembly. Such an assembly is used in a pair—one on each side of an opening, and on each floor.
Anchor bolt
(d) Hold-down bolt assembly

FIGURE 6 Sliding and overturning of a shear wall.

UPLIFT ON ROOFS DUE TO WIND OR EARTHQUAKE

The interaction between horizontal diaphragms and shear walls means that if any one of these elements fails, the entire structure may collapse. Because of its light weight, a frequent cause of the failure of a WLF building is the blowing off of the roof due to uplift forces created by wind. Once the roof blows off, complete collapse of the structure becomes imminent. Therefore, it is important to ensure that the roof assembly in a WLF building is adequately held down.

In other words, roof sheathing should be securely nailed to the rafters, and the rafters should be securely fastened to the wall's double top plate. In a high-wind or seismic region, the rafters are generally required to be anchored to the top plate with sheet-metal anchors, referred to as *hurricane* or *seismic straps*, Figure 7. Additional sheet steel straps may be required in a high-wind or seismic region to provide a continuous load path from the roof to the foundation, Figure 8.

WLF BUILDING—A LOAD-BEARING WALL STRUCTURE

The structural behavior of a WLF building just described shows that all the major elements of a building work together in countering lateral loads. The interaction between horizontal diaphragms and shear walls in a building is not peculiar to a WLF construction. It applies to all structures—reinforced concrete frame, load-bearing masonry, or steel frame structure.

Because most walls in a WLF building double as gravity-load-resisting and shear walls, a WLF building is, in fact, a load-bearing-wall building. In other words, there is no fundamental difference between the structural behavior of a load-bearing masonry or concrete building and that of a contemporary WLF building. The reason for referring to it as a wood *light-frame* building is that the walls consist of a frame instead of solid concrete or masonry walls.

PRINCIPLES IN PRACTICE

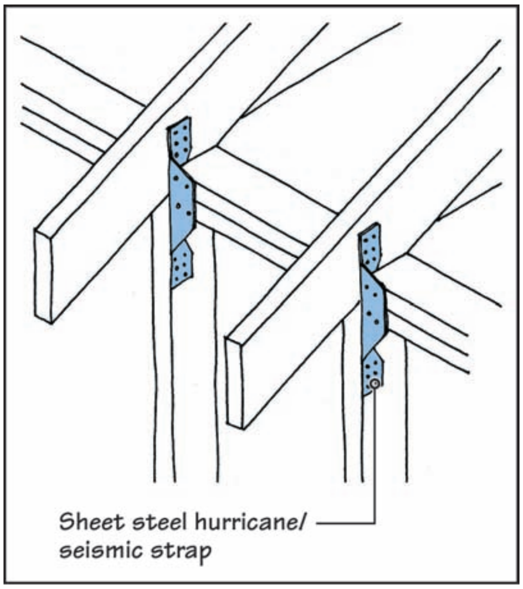


FIGURE 7 Commonly used hurricane/seismic straps for a roof.

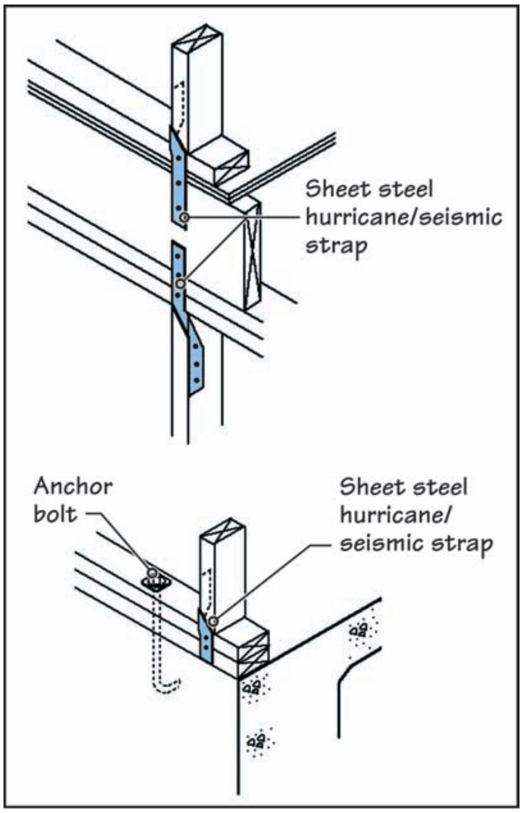


FIGURE 8 Commonly used hurricane/seismic straps to provide a continuous load path from the roof to the foundation.

PRACTICE **QUIZ**

Each question has only one correct answer. Select the choice that best answers the question.

38. In referring to a floor or roof of a building as a *horizontal diaphragm*, the reference is with respect to
- **a.** gravity loads.
- **b.** lateral loads.
- **c.** both gravity and lateral loads.
- **d.** none of the above.

39. Hold-down bolts, when provided in a WLF wall building, are used in
- **a.** floors.
- **b.** walls.
- **c.** the roof.

40. A wood light-frame building is essentially a
- **a.** load-bearing-wall structure.
- **b.** frame structure.

EXPAND YOUR KNOWLEDGE

Wood Construction Prior to Balloon Frame

Ignoring some primitive precedents such as the tepee—a cone of wood poles covered with hides—or a pit dwelling roofed with wood beams and thatch or hides, wood construction in the United States developed from the early log construction to the present-day platform frame construction. As discussed in Section 15.1, platform frame construction evolved quickly and seamlessly from its predecessor, balloon frame construction. The wood construction that existed immediately prior to the balloon frame was, however, vastly different from it.

The purpose of this section is to provide a brief background on pre-balloon frame wood construction techniques (using heavy timber members) to help the reader visualize the radical change brought about by balloon frame construction. In addition, because pre-balloon frame construction has recently seen a renaissance, this section also gives a brief account of the pre-balloon frame's contemporary incarnation.

Types of Heavy Timber Frame

Prior to the invention of the balloon frame, that is, until the mid-nineteenth century, the structural members of wood frame buildings in the United States ranged in thickness from 6 in. to 10 in., and even larger in some instances. Compare these dimensions with those of balloon frame members, which were nominally 2 in. thick. In other words, the construction system that

(*Continued*)

existed before the balloon frame used heavy sections of wood. We refer to this construction system as *heavy timber construction* or *timber frame construction*. (In Section 13.9, *timbers* are defined by contemporary construction standards as wood members with both nominal cross-sectional dimensions greater than or equal to 5 in.)

It is because of the substantial difference between the cross-sectional dimensions of timber frame members and those of the balloon frame that the balloon frame came to be known as *wood light-frame construction*. Two types of timber frame systems, differing in terms of their lateral-force resisting mechanisms, were common:

- Timber frame with exterior masonry walls
- Braced timber frame

Timber Frame With Exterior Masonry Walls

This system consisted of load-bearing exterior walls of brick or stone with an interior structure consisting of (heavy) timber beams and columns. The floor framing consisted of thick lumber planks or tongue-and-groove lumber decking, and roof framing was either flat or pitched and also consisted of heavy timber.

This version of timber framing came to be known as *mill construction* because the factories of that era (producing textiles, shoes, and other consumer items) built with this system could obtain insurance coverage against fire. Mill construction was recognized as slow-burning, providing greater fire resistance than the alternative available at the time, which consisted of exterior masonry walls with interior framing comprising wrought iron (or cast iron) beams and columns. (See Sections 7.2 and 7.5, which highlight the greater fire resistance of heavy timber members compared with that of unprotected iron or steel. Spray-on fire protection, currently used on steel frames, did not exist at the time.)

Mill construction was used for nonfactory occupancies as well—commercial, institutional, and storage buildings. In this construction system, the exterior walls provide both gravity load resistance and lateral load resistance. With all the lateral load resistance provided by masonry walls, the interior columns need to resist only gravity loads. An example of historic mill construction, used for a commercial building completed in 1901, is shown in Figure 1.

A construction system quite similar to historic mill construction is also used today and is referred to by the International Building Code (IBC) as *Type IV, heavy timber (HT) construction*. Although a *timber* is defined as a member with minimum nominal lumber dimensions of 5 × 5, heavy timber (Type IV) construction is further qualified by the IBC as one in which the minimum nominal lumber dimensions are 6 × 10 for floor beams, 6 × 8 for roof beams, 8 × 8 for columns of a multistory building, 6 × 8 for columns of a single-story building, and so on.

As shown in Table 7.1, Type IV construction does not allow concealed spaces in the structural frame (such as the spaces between studs or floor joists in WLF construction), that is, the timber members are exposed. Exterior load-bearing walls, when provided, must be of noncombustible materials with a minimum 2-h fire rating.

The salient features of contemporary Type IV construction are shown in Figure 2, and a few representative details are given in Figure 3. The difference between historic mill construction and Type IV construction is that the connections between connecting beams, between beams and columns, and between beams and walls use hardware made of steel and are more sophisticated than the cast iron or wrought iron hardware used in mill construction. Another difference is that in contemporary Type IV construction, engineered lumber, such as glulam, is more commonly used than solid sawn lumber.

Braced Timber Frame

Braced timber frame construction is similar to Type IV or mill construction but without the exterior load-bearing walls. In the absence of walls that provided lateral load resistance in mill construction, a braced timber frame depended on inclined (knee) braces and close-fitting joints between the members of the frame. Because knee braces could not provide the same degree of lateral resistance as masonry walls, a braced timber frame was generally used for one- or two-story buildings—individual residences, barns, and small commercial buildings.

A typical braced timber frame used at the time is shown in Figure 4. The framing varied because several variations of the system existed, depending on the scale of the building, its occupancy, and regional preferences. The primary structural components of the building consisted of semirigid wood frames called *bents*.

Most dwellings were small. Therefore, each bent was typically 20 ft to 25 ft wide, spaced about 12 ft to 15 ft apart. Thus, the structure shown in Figure 4, consisting of four bents (three bays), is about 40 ft long. A fireplace, built of brick or stone,

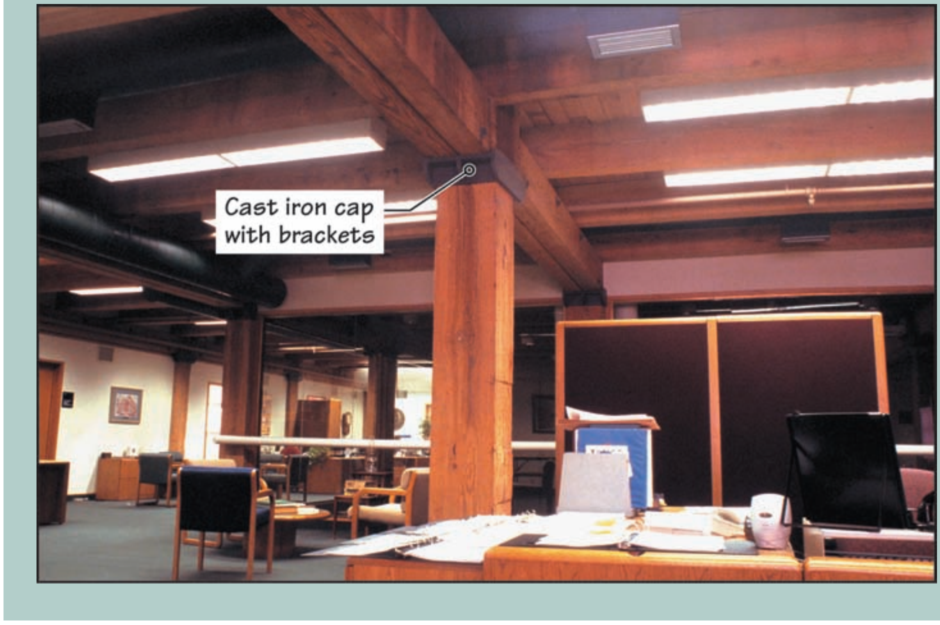


FIGURE 1 The interior of the second floor of the historic Texas School Book Depository Building in Dallas, Texas, illustrates the typical mill construction used for a commercial building. This seven-story building was built in 1901, with heavy timber beams and columns (approximately 15 in. × 15 in.) and brick walls about 30 in. thick at the ground floor. The sixth floor of the building was used to assassinate President John F. Kennedy in 1963. The building is being preserved for its historic importance, and the lower floors of the building are currently used by the Dallas County Administration.

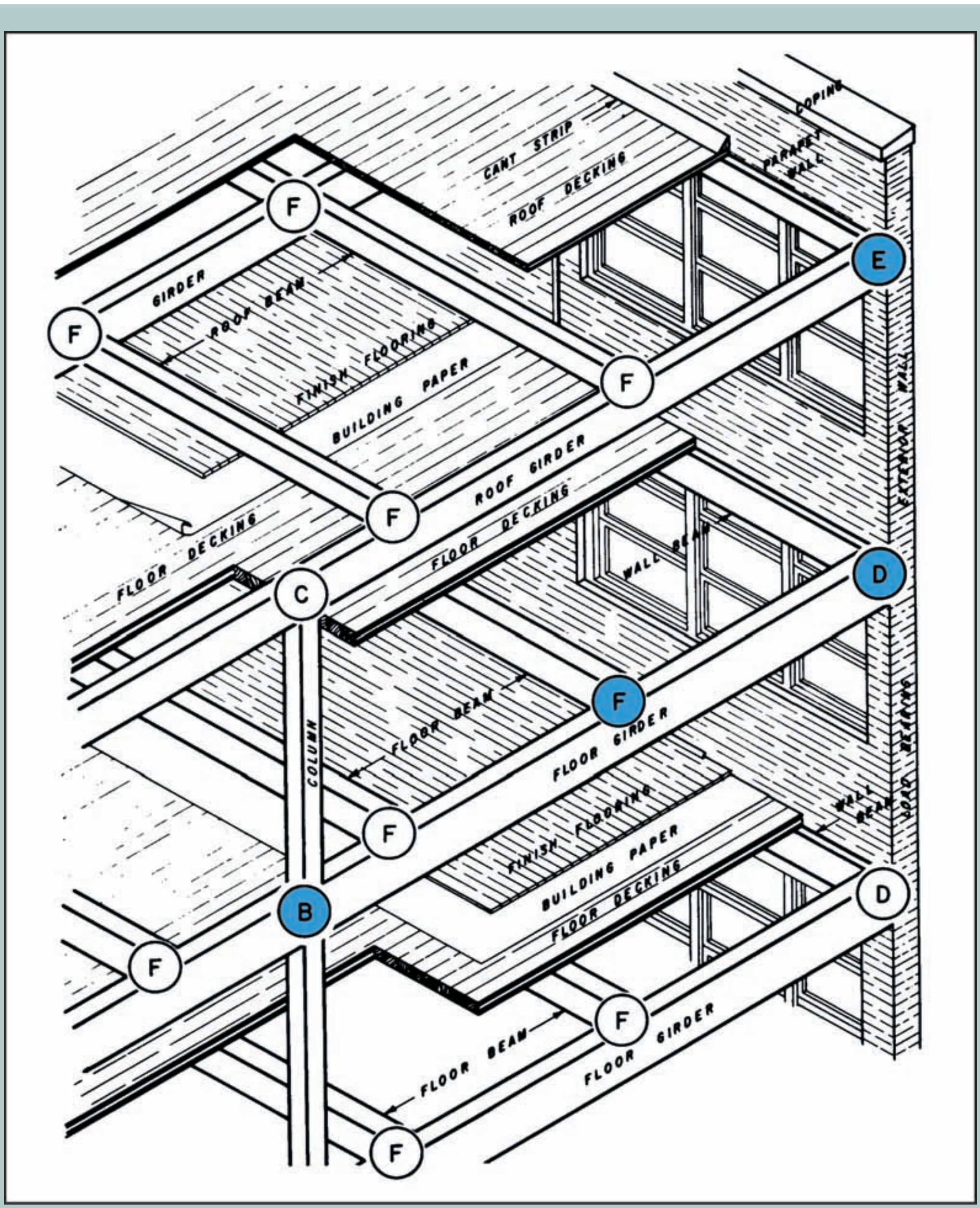

COPING
PARAPET WALL
CANT STRIP
ROOF DECKING
F
E
GIRDER
ROOF BEAM
F
FINISH FLOORING
BUILDING PAPER
F
EXTERIOR WALL
ROOF GIRDER
F
FLOOR DECKING
FLOOR DECKING
WALL BEAM
C
D
COLUMN
FLOOR BEAM
F
FLOOR GIRDER
LOAD BEARING WALL
WALL BEAM
F
FINISH FLOORING
BUILDING PAPER
B
FLOOR DECKING
D
F
F
FLOOR BEAM
FLOOR GIRDER
F

FIGURE 2 The typical arrangement of structural members in Type IV heavy timber (HT) construction is almost identical to that of the (historic) mill construction. Figure 3 shows a few details of this system. For a more comprehensive discussion of HT construction, refer to Publication WCD5, *Heavy Timber Construction*, by the American Wood Council. The publication can be viewed in PDF format at http://www.awc.org/pdf/wcd5.pdf. (Illustration courtesy of the American Wood Council, Leesburg, Virginia)

forming the main feature of the dwelling, was located between the two interior bents.

Each bent consisted of two inclined rafters, a beam at the intermediate floor, a (sill) beam at the foundation level, and knee braces for lateral load resistance, Figure 5(a). The members of each bent were called *principal members*, for example, *principal post*, *principal rafter*, *principal floor beam*, and *principal sill beam*. The beam that resists the lateral thrust in the rafters (i.e., ties the rafters together) was appropriately called the *tie beam* or *crossbeam*.

A bent cannot stand up on its own. Two or more bents (generally identical in configuration) must be joined along the length of the building to make a stable three-dimensional structure. These joints are provided by a longitudinal sill beam at the foundation level, and by floor and roof beams at the floor and roof levels, respectively, Figure 5(b). Floor joists placed between principal sill beams and principal floor beams further add to the stability of the structure (see Figure 4).

NOTE

What Is a Bent?

A bent is an assembly of linear structural members, all of which lie in a vertical plane that is perpendicular to the ridge. The term *bent* is not in common use in contemporary literature because it has been replaced by the term *frame*. In other words, the terms *two-dimensional frame* and *bent* may be used interchangeably.

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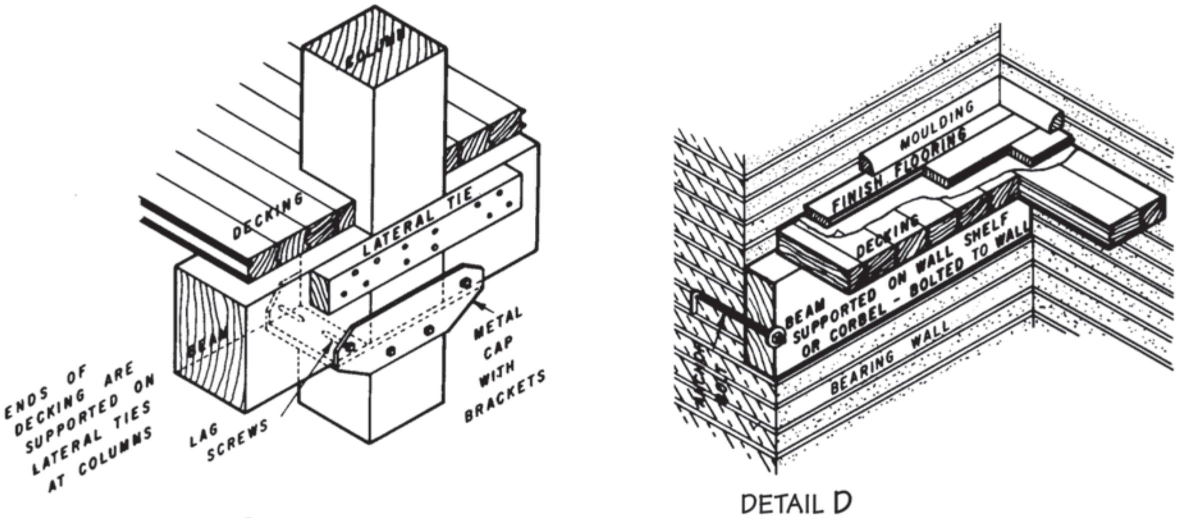
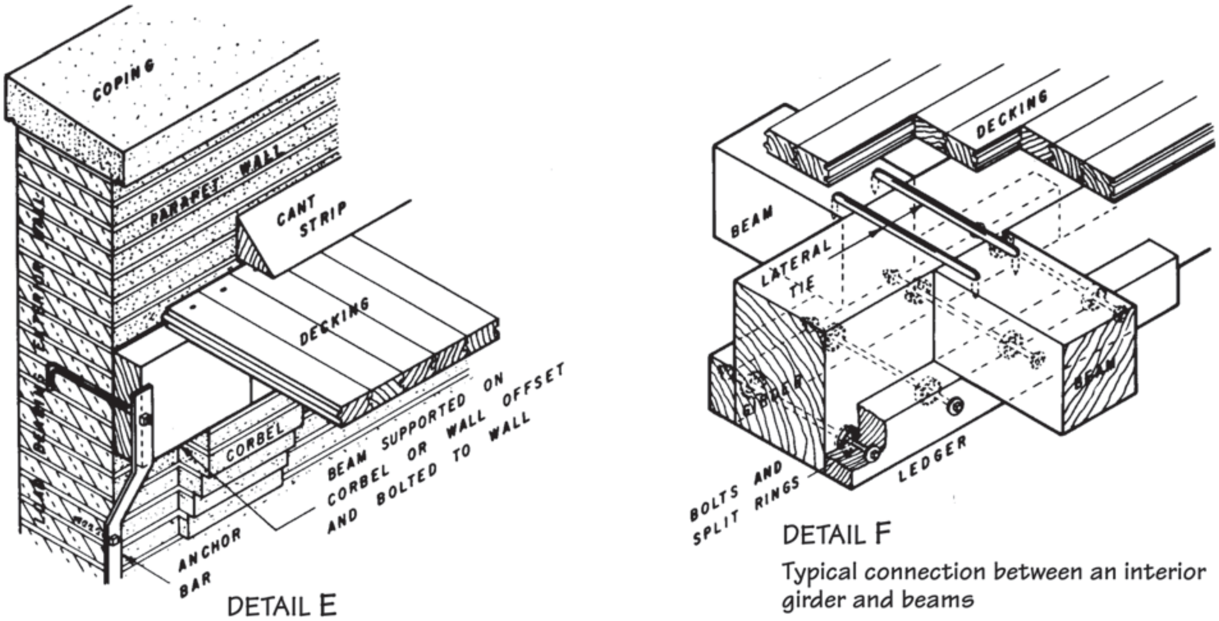

COLUMN
DECKING
LATERAL TIE
BEAM
METAL CAP WITH BRACKETS
LAG SCREWS
ENDS OF DECKING ARE SUPPORTED ON LATERAL TIES AT COLUMNS
MOULDING
FINISH FLOORING
DECKING
BEAM SUPPORTED ON WALL SHELF OR CORBEL - BOLTED TO WALL
BEARING WALL

DETAIL B

Typical connection between column and beam

DETAIL D

Typical connection between spandrel floor beam and exterior masonry wall


COPING
PARAPET WALL
CANT STRIP
DECKING
BEARING EXTERIOR WALL
CORBEL
BEAM SUPPORTED ON CORBEL OR WALL OFFSET AND BOLTED TO WALL
ANCHOR BAR
DECKING
BEAM
LATERAL TIE
GIRDER
BEAM
LEDGER
BOLTS AND SPLIT RINGS

DETAIL E

Typical connection between spandrel roof beam and exterior masonry wall

DETAIL F

Typical connection between an interior girder and beams

FIGURE 3 Typical details used in Type IV HT construction, similar to historic mill construction. The details are keyed to Figure 2. For a more comprehensive discussion of HT construction, refer to Publication WCD5, *Heavy Timber Construction*, by the American Wood Council. The publication can be viewed in PDF format at http://www.awc.org/pdf/wcd5.pdf. (Illustrations courtesy of the American Wood Council, Leesburg, Virginia).

At the roof level, various alternatives were used to connect the bents using a ridge beam and (or) purlins. The framing shown in Figure 4 and 5(b) uses *purlins* that span between the principal rafters. The purlins support wood decking that runs parallel to the rafters. The lattice formed by the purlins and decking adds to the structural stability at the roof. The exclusion of a ridge beam simplified the joinery at the ridge because the joint only needed to accommodate the two opposite rafters. For the same reason, the tie beam was placed slightly below the eave in many cases, Figure 6.

Joints Between Framing Members

The profile of each joint between the members of the timber frame is particularly important because no metal connection hardware or fasteners were available. Not only was the framing geometry modified to obtain a suitable joint detail, but the cross-sectional dimensions of framing members were often dictated by joint detail rather than member spans or loads.

The most versatile joint profile between the members is the *mortise-and-tenon joint*, in which the mortise (slot) in one

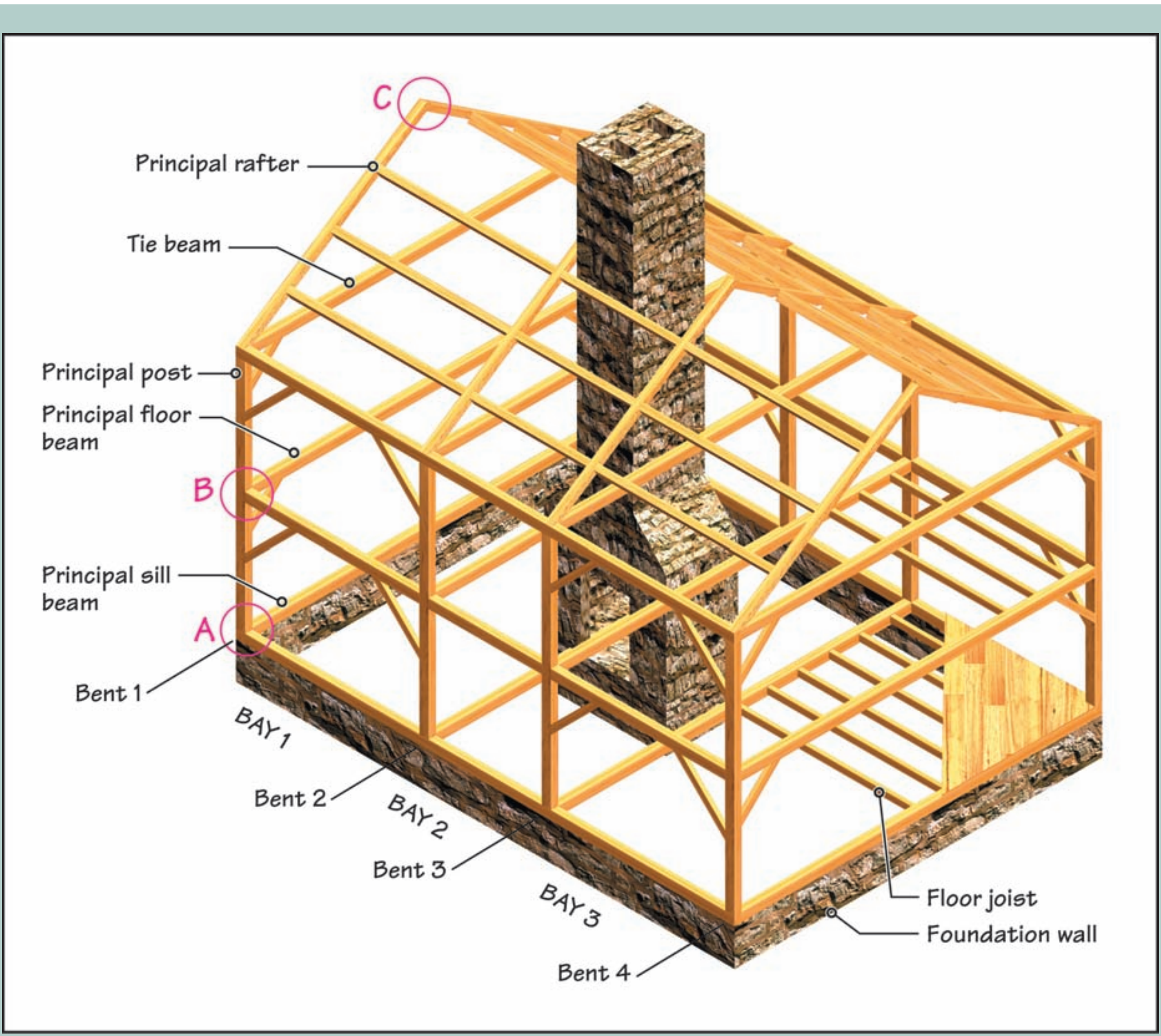
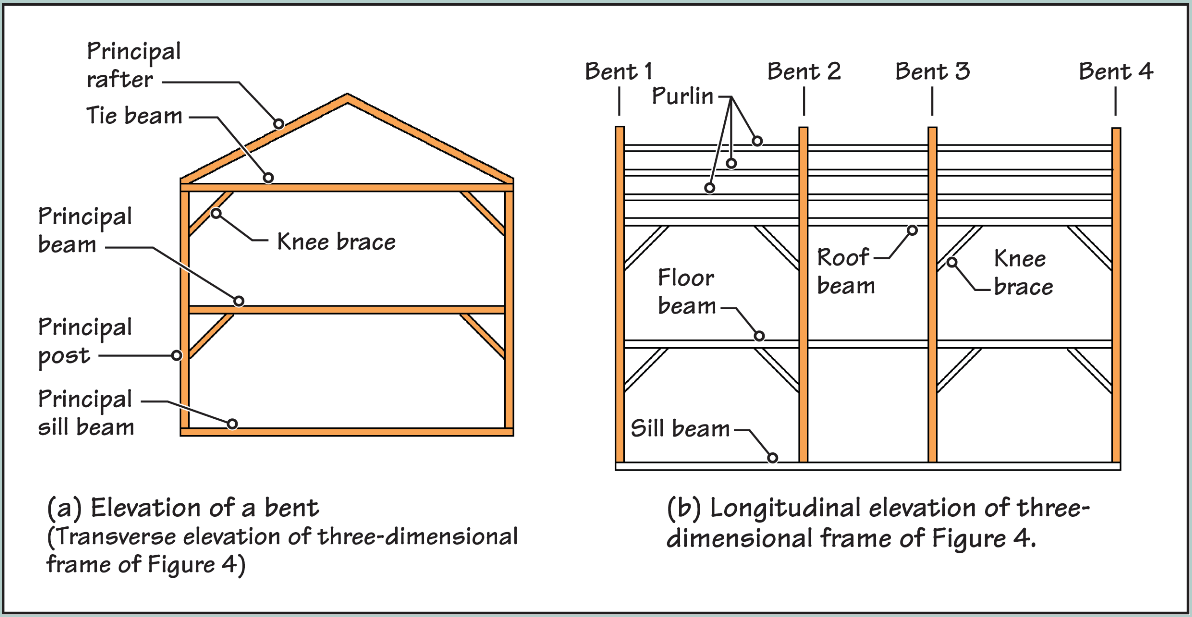

C
Principal rafter
Tie beam
Principal post
Principal floor beam
B
Principal sill beam
A
Bent 1
BAY 1
Bent 2
BAY 2
Bent 3
BAY 3
Bent 4
Floor joist
Foundation wall

FIGURE 4 A typical (historic) braced timber frame.


Principal rafter
Tie beam
Principal beam
Knee brace
Principal post
Principal sill beam
Bent 1
Bent 2
Bent 3
Bent 4
Purlin
Roof beam
Floor beam
Knee brace
Sill beam

(a) Elevation of a bent
(Transverse elevation of three-dimensional frame of Figure 4)

(b) Longitudinal elevation of three-dimensional frame of Figure 4.

FIGURE 5 Transverse and longitudinal elevations of the three-dimensional timber frame shown in Figure 4 with commonly used nomenclature for various members.

member accepts the tenon (tongue) from the opposite member. Most joints in a braced timber frame are some version of this joint.

The joints in a timber frame must be tight and close-fitting so that they lock the members of the frame together. Expert carpenters and joiners were needed to make precise joints. Wooden pegs were used to increase the tensile strength of the joint, and wedges were used for joint tightness.

Both pegs and wedges helped maintain joint tightness even after the building's construction. As the (heavy) wood sections

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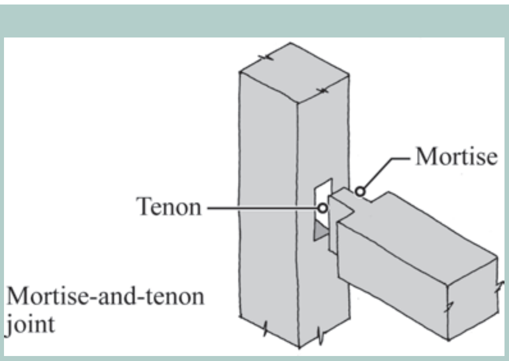

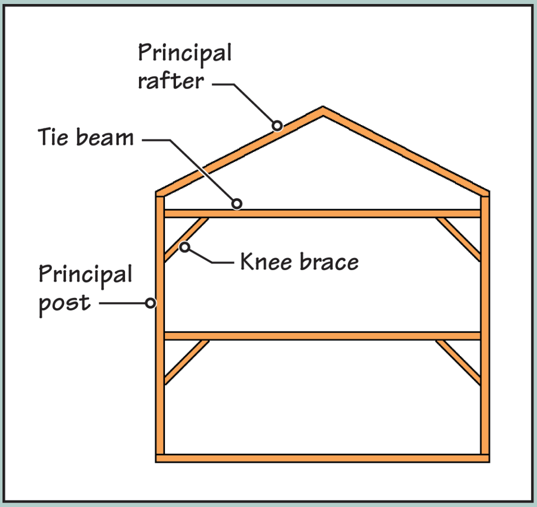

FIGURE 6 Elevation of a bent with a tie beam placed below the eave to simplify the joints between tie beam, rafter, and principal post.

changed from their original "green" condition to equilibrium moisture content, the joints lost some tightness, a problem that was overcome by hammering the pegs and wedges in. A few examples of joint details in a braced timber frame are shown in Figures 7 to 9. These details are keyed to the frame of Figure 4.

Erection of a Braced Timber Frame

Each bent was generally assembled flat on the ground, raised to the vertical orientation, and lifted into position to bear on the masonry foundation wall. Generally, when all bents were completed, a day was fixed for tilting and lifting the bents to the required locations. On this day, the entire community would assemble to help in the effort [Ref. 15.2]. As the bents were raised, they were supported by temporary braces, which allowed the longitudinal framing members to be connected to them.

Frame Infill and Finishes

In order to provide a support surface for finish materials, infill systems were attached to the frame to form walls, floors, and (in some cases) roofs. For the walls, studs were used as infill members. On the interior surface, the studs were covered with *wattle and daub* [Ref. 15.3]. Wattle consisted of small horizontal and vertical pieces (scantlings) joined together in a basket-weave pattern. This served as what is now called *lathe*.

The wattle was plastered with clay reinforced with horsehair. (The term *daub* was then used for plaster.) In later times, the space between the studs was filled with brick masonry or sand-lime plaster over wattle. The exterior finish on the studs was generally horizontal wood boards, called *clapboard*, which is similar to contemporary wood lap siding. The floors were finished with wood boards pegged to joists.

The Renaissance of Braced Timber Frame

The historic braced timber frame construction, described in the previous section, has recently seen a revival in North America by builders who have revived the craft, lost to us for about two centuries. Figures 10 and 11 illustrate the use of timber frame in contemporary dwellings. As shown, the exposed structural members

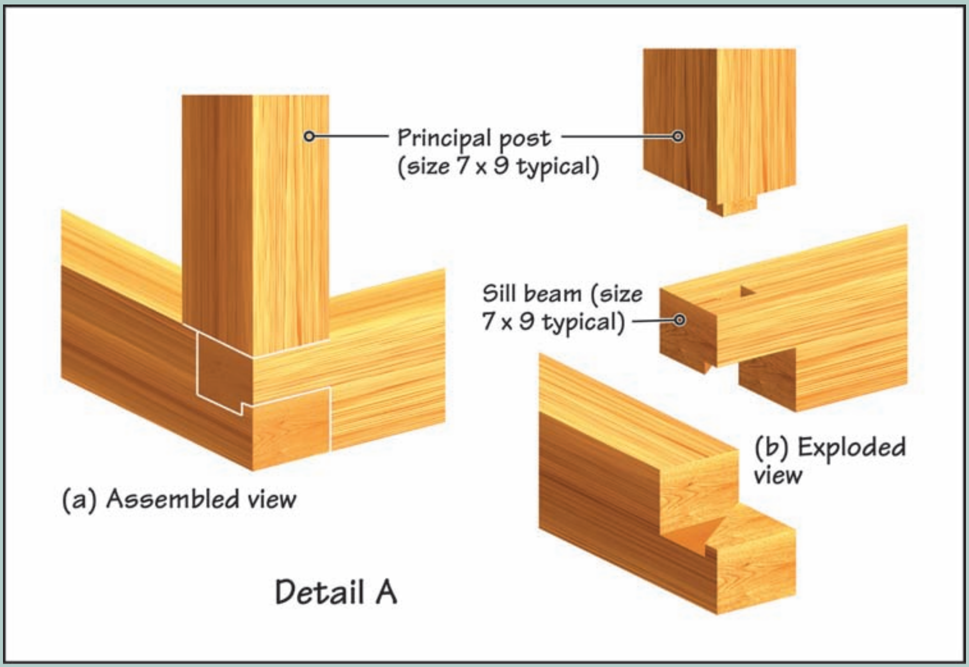

FIGURE 7 Detail of the joint between (corner) principal post and sill beams from two directions. The joint between the post and sill beam is a mortise-and-tenon joint; the joint between the sill beams is a complex form of lap joint. (Keyed to Figure 4.)

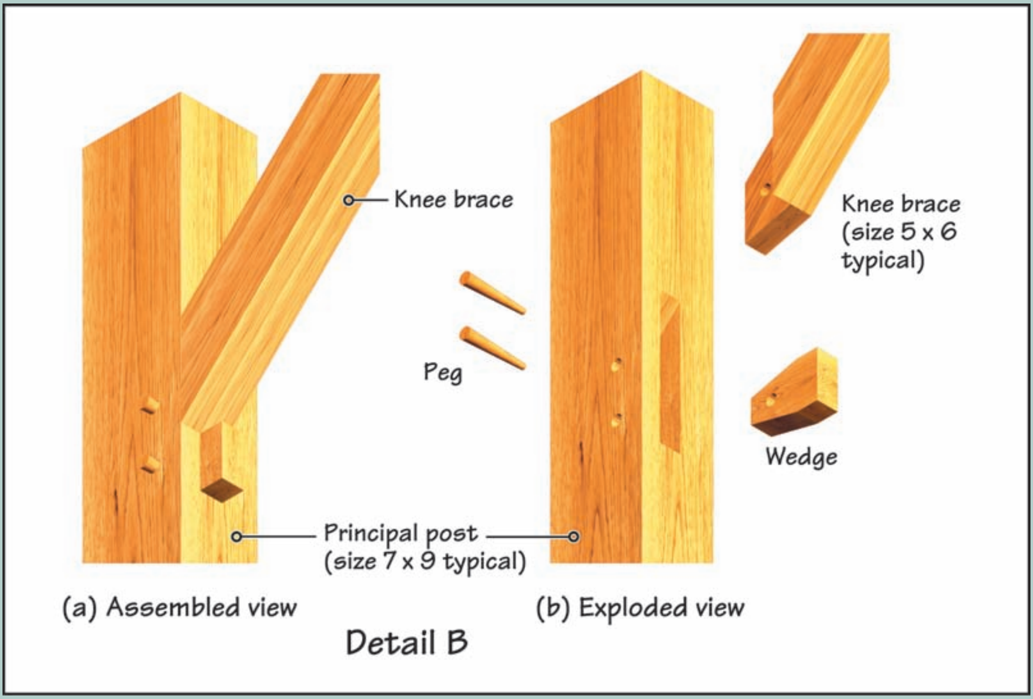
Knee brace
Peg
Principal post (size 7 x 9 typical)
Knee brace (size 5 x 6 typical)
Wedge
(a) Assembled view
(b) Exploded view
Detail B

FIGURE 8 Detail of the (mortise-and-tenon) joint between a principal post and a knee brace. Notice the use of pegs and wedges in the joint. (Keyed to Figure 4.)

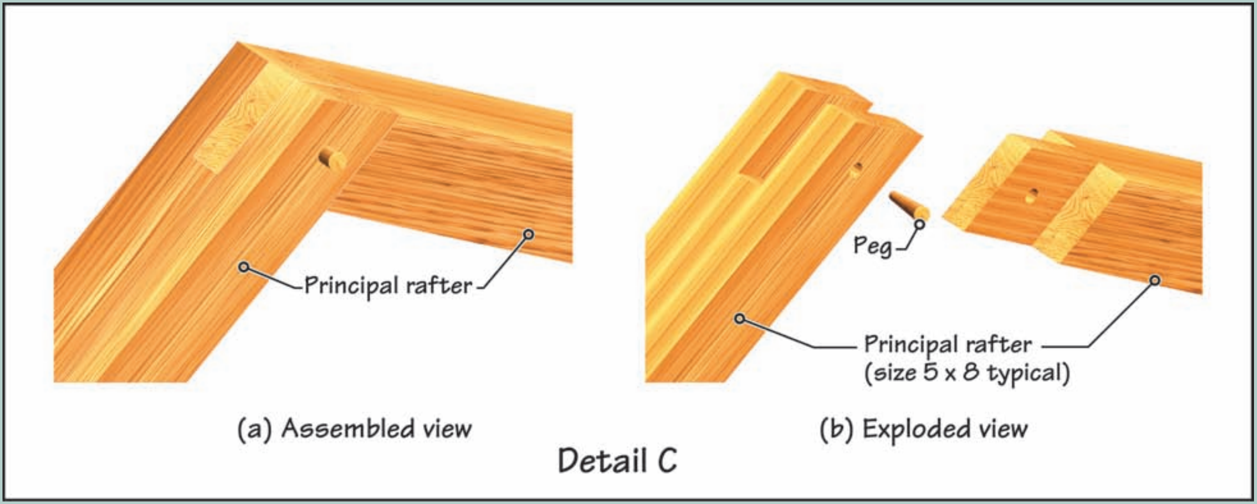

FIGURE 9 Detail of the (open mortise-and-tenon) joint between the opposite principal rafters; the joint between common rafters is similar. (Keyed to Figure 4.)

of the timber frame (posts, beams, rafters, and knee braces) impart a sense of strength and durability to the interior. The wood grain further enhances the structure's appeal.

Although contemporary timber frame construction shares much with its historic precedent, it has adapted to today's technology and design requirements. The sophistication of modern woodworking machine tools and hoisting equipment (to raise and install the bents in position) has greatly improved contemporary timber frame construction. Computer-aid design and manufacturing (CAD/CAM) technology has allowed all carpentry and joinery to be automated, and the application of modern structural engineering knowledge has reduced framing member sizes.

Another major difference lies in the provision of lateral load resistance in the structure. Our knowledge of lateral loads (their magnitude and how they are resisted by buildings) has advanced considerably in the past few decades. As a result, contemporary building codes require much greater lateral load–resisting capacity than that provided by knee braces.

Although knee braces are used in the modern timber frame building, they are not relied upon to provide lateral load resistance. Their main purpose is to square up the frame and to provide frame stability during erection. Contemporary timber frames are provided with shear walls or a similar lateral load–resisting strategy.

Yet another difference is in the use of structural insulated panels (SIPs) to provide the envelope of a modern timber frame building, that is, the panels constitute the exterior walls and roof of a timber frame building. This eliminates the use of infill studs in walls and purlins in the roof. With their expanded polystyrene (EPS) foam sandwiched between two $\frac{1}{2}$-in.-thick OSB boards, SIP

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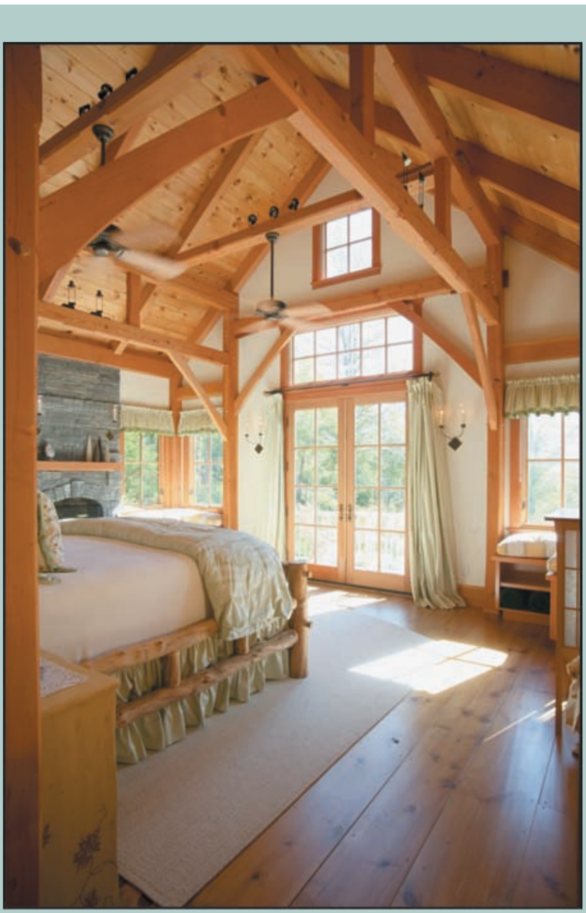


FIGURE 10 The interior of a typical contemporary timber frame residence. (Photo courtesy of Bensonwood Inc.)

panels provide sheathing for the exterior wall finish, envelope insulation, and a substrate on which interior gypsum drywall can be applied (see Chapter 17 for a discussion of SIP).

The difference between SIPs (described in Chapter 17) and those required for use with timber frame is that the latter generally do not carry gravity loads because that function is performed by the timber frame. The panels in timber frame serve as wall and roof sheathing and as shear walls. SIP panels with EPS (or XPS) foam core insulation, sandwiched between OSB on the panel's exterior face and gypsum board on its interior face, are available. (See Chapter 5 for a discussion of EPS and XPS insulation.)

Because the panels are placed outside of the timber frame, the structure and the envelope of the building are completely independent. Additionally, because of the foam core, the structural frame is insulated from the exterior with minimal thermal breaks. This contrasts with the conventional WLF, in which the insulation is discontinuous, interrupted by the structural members (studs and rafters), compromising the building's energy efficiency.

Modern Timber Frame and Heavy Timber (Type IV) Construction

It must be recognized that modern timber frame construction generally does not qualify as heavy timber (Type IV) construction because it does not satisfy code requirements for that construction with respect to minimum member sizes and exterior wall construction. Thus, in general, a modern timber frame building is a Type V construction.

Modern Timber Frame and Sustainability

The use of SIP panels in the envelope of a timber frame building makes it energy efficient, improving its sustainability. The use of glulam or other engineered wood in place of solid sawn lumber adds to the performance and sustainability of modern timber frame. Glulam and other engineered lumber, as described in Chapter 14, are dried to a moisture content of 15% or less. solid sawn timbers, on the other hand, are used in the green state (moisture content of 20% or more). This implies that the glulam frame shrinks or moves considerably less than the solid sawn timber frame, providing greater envelope tightness. (See Chapter 14 for additional comments on the sustainability of engineered lumber.)

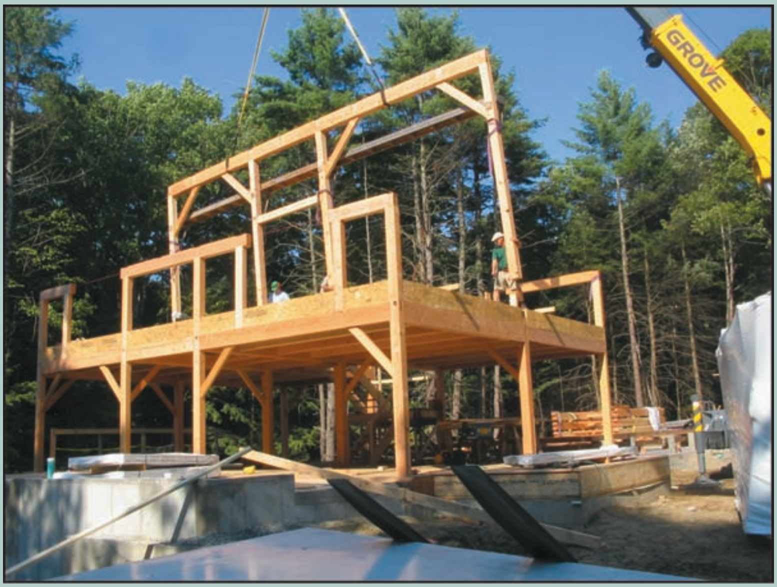


FIGURE 11 A timber frame residence under construction showing a prefabricated bent (frame) being installed. (Photo courtesy of Bensonwood Inc.)

REVIEW QUESTIONS

1. Explain why we use 12 in., 16 in., or 24 in. as center-to-center spacing of framing members in a wood light-frame structure.
2. Explain why the top plate in a wall assembly is generally made of two 2-by members.
3. Using sketches and notes, explain how the two top plate members are connected at a wall (a) corner and (b) T-junction.
4. Using a sketch, show the typical detail of anchorage of a sill plate to the foundation.
5. Show in plan at least two alternative arrangements of studs at a wall corner.
6. Sketch in elevation the typical arrangement of studs around a wall opening. Name all the important framing members.
7. Using a three-dimensional sketch and notes, explain the composition of a typical header over an opening in a wall made of 2 × 6 studs.
8. Explain the difference between a ridge board and a ridge beam and indicate where each is required.
9. With the help of three-dimensional sketches, show the configuration of a (a) gable-end roof, (b) hip-end roof, and (c) lean-to (shed) roof.
10. Describe in general what sheathing is. Which components of a wood frame building need sheathing?
11. Describe various functions of wall sheathing in a wood light-frame building.

CHAPTER 16

Wood Light-Frame Construction–II

CHAPTER OUTLINE

16.1 EXTERIOR WALL FINISHES IN A WLF BUILDING

16.2 HORIZONTAL SIDINGS

16.3 VERTICAL SIDINGS

16.4 FINISHING THE EAVES, RAKES, AND RIDGE

16.5 GYPSUM BOARD

16.6 INSTALLING AND FINISHING INTERIOR DRYWALL

16.7 FIRE-RESISTANCE RATINGS OF WLF ASSEMBLIES

The previous chapter focused on the framing aspects of a WLF construction system. This chapter deals with some of the important interior and exterior finishes used in this system. It begins with a brief introduction to various exterior wall finishes typically used in a WLF building. This is followed by a detailed discussion of various types of siding that are unique to WLF (or light-gauge steel frame) buildings.

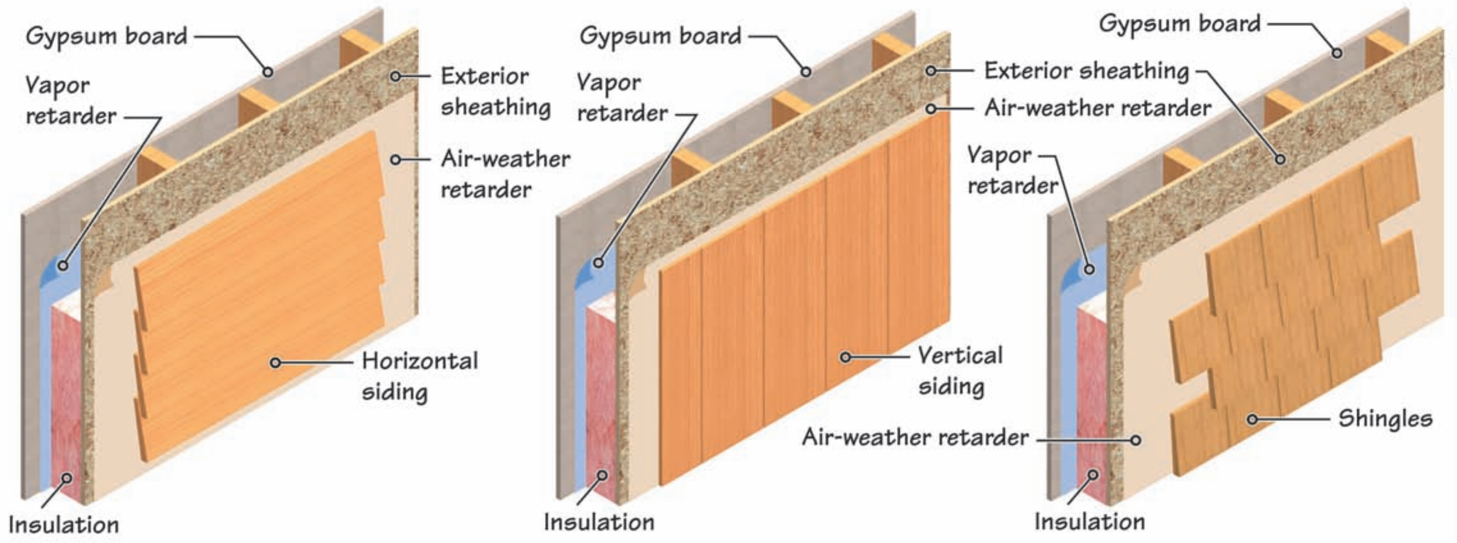
Other exterior wall finishes, such as stucco, the exterior insulation and finish system (EIFS), and brick veneer are described in later chapters because they are used in all types of construction systems. For the same reason, floor finishes and roof coverings for WLF buildings are discussed in later chapters—floor finishes in Chapter 36 and roof coverings in Chapters 33 and 34. Stair construction is covered in Chapter 35.

An introduction to gypsum board as an interior-wall and ceiling finish material is provided in this chapter, which concludes with a discussion of the fire-resistance ratings of WLF assemblies.

16.1 EXTERIOR WALL FINISHES IN A WLF BUILDING

Various exterior wall finishes can be applied to a WLF building. As shown in Figure 16.1, the more commonly used finishes are:

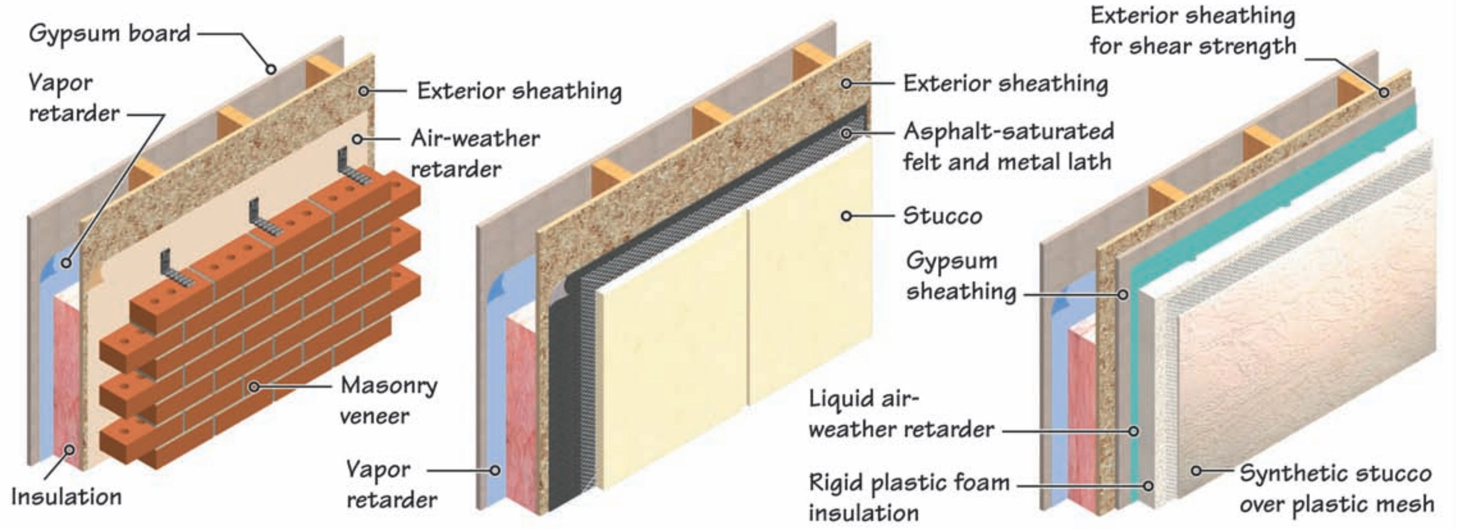
- Horizontal siding
- Vertical siding (diagonal siding, used occasionally)
- Shingles
- Masonry veneer
- Portland cement stucco
- Exterior insulation and finish system (EIFS), also called synthetic stucco


Gypsum board
Vapor retarder
Exterior sheathing
Air-weather retarder
Horizontal siding
Insulation
Gypsum board
Vapor retarder
Vertical siding
Air-weather retarder
Insulation
Gypsum board
Exterior sheathing
Air-weather retarder
Vapor retarder
Shingles
Insulation

(a) Horizontal siding
Covered in this chapter

(b) Vertical siding
Covered in this chapter

(c) Shingles


Gypsum board
Vapor retarder
Exterior sheathing
Air-weather retarder
Masonry veneer
Insulation
Vapor retarder
Exterior sheathing
Asphalt-saturated felt and metal lath
Stucco
Gypsum sheathing
Liquid air-weather retarder
Rigid plastic foam insulation
Exterior sheathing for shear strength
Synthetic stucco over plastic mesh

(d) Masonry veneer
See Chapter 28

(e) Portland cement stucco
See Chapter 29

(f) Synthetic stucco (EIFS)
See Chapter 29

FIGURE 16.1 Commonly used finishes on WLF exterior walls.

Only horizontal and vertical sidings are discussed in this chapter. Masonry veneer is discussed in Chapter 28, and stucco and EIFS are discussed in Chapter 29. The use of shingles is costly and relatively uncommon these days and is not included in this text. Two or more of these finishes may be used either on the same facade or on different facades of the same building.

16.2 HORIZONTAL SIDINGS

Horizontal siding, a commonly used exterior wall finish in WLF buildings, consists of long overlapping strips of material nailed to the studs. Some siding manufacturers also allow their siding to be nailed to a nailable wall sheathing such as OSB. Because the siding strips overlap, they shed water, and the horizontal lines on the facade are accentuated under direct sunlight. Commonly used materials for horizontal siding are:

- Wood
- Plywood
- Hardboard
- Fiber-cement
- Vinyl
- Metal (aluminum and steel are common)

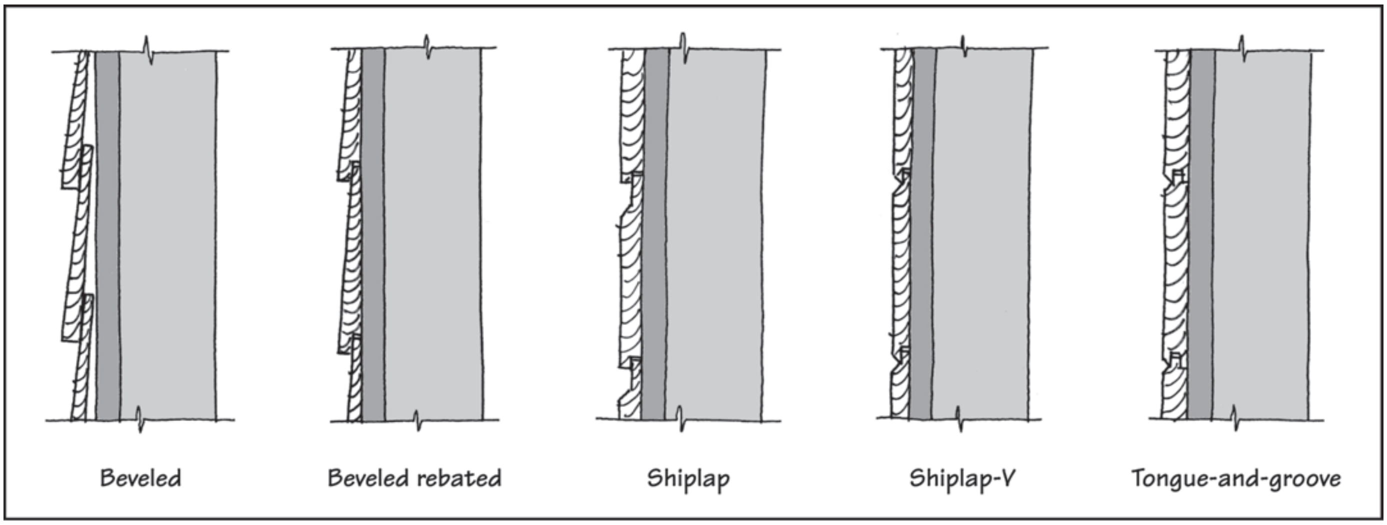
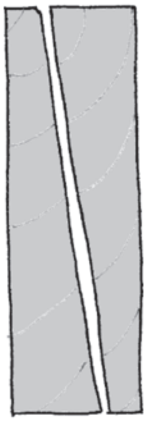

Beveled
Beveled rebated
Shiplap
Shiplap-V
Tongue-and-groove

FIGURE 16.2 A few of the several horizontal wood siding profiles.

HORIZONTAL WOOD SIDING PROFILES

Wood siding is available in various profiles and several widths (from 6 in. to 12 in. nominal) and in a thickness that generally increases with the width of the siding, Figure 16.2. Lengths of up to 16 ft are common.

Wood species commonly used are cedar, redwood, and cypress because of their greater decay resistance. Other species used are sugar pine, white pine, and ponderosa pine because of their resistance to warpage. Manufacturers provide the details to be used in applying their siding, which are generally similar to those used for applying beveled wood siding, described at length in this section.



Beveled siding is made by sawing a rectangular piece of wood into two pieces.

BEVELED WOOD SIDING

The cross section of a piece of beveled wood siding (also called *clapboard*) is tapered, so that one end is thicker than the other. It is generally made by sawing a rectangular piece of lumber into two pieces. Typical siding widths range from 6 in. to 10 in. (nominal). Thicknesses range from $\frac{1}{2}$ in. to $\frac{3}{4}$ in., depending on the width of the siding.

One face of siding is generally rough, and the other face is smooth surfaced. That is why most manufacturers make beveled wood siding as S1S2E. Beveled siding is applied with the thicker side down; the upper siding overlaps the lower siding, Figure 16.3.

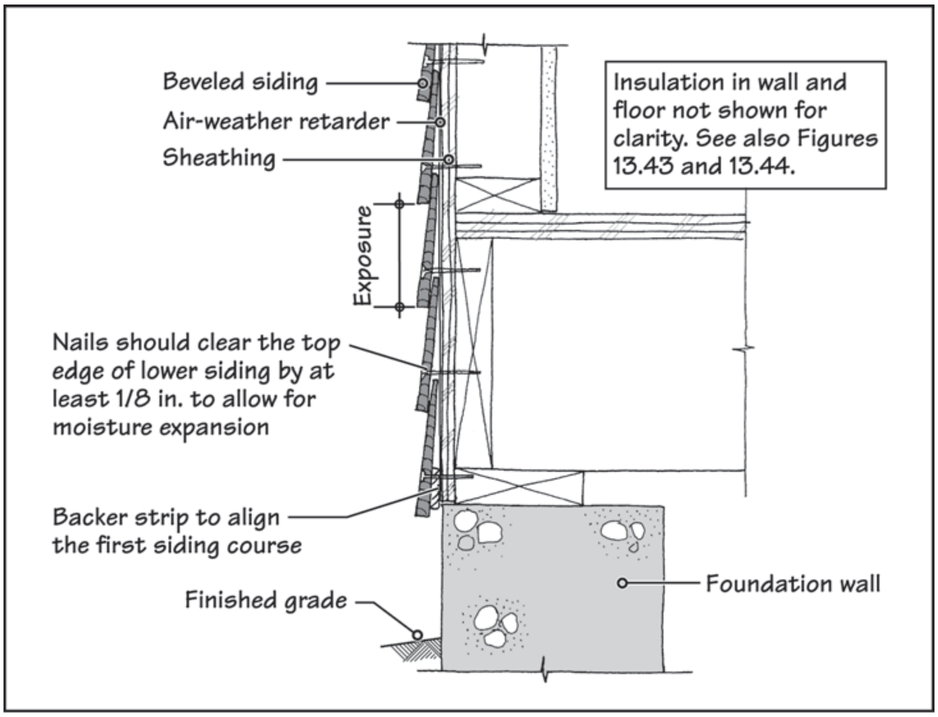

Beveled siding
Air-weather retarder
Sheathing
Insulation in wall and floor not shown for clarity. See also Figures 13.43 and 13.44.
Exposure
Nails should clear the top edge of lower siding by at least 1/8 in. to allow for moisture expansion
Backer strip to align the first siding course
Finished grade
Foundation wall

FIGURE 16.3 Typical section at the foundation level of a wall with beveled wood siding as exterior wall finish.

The exposed width of siding is called *exposure*, which simply equals the width of siding minus the overlap. The manufacturer-recommended overlap varies from 1 in. to $1\frac{1}{2}$ in. The overlap may be adjusted slightly, even on the same facade, to match the window sill elevation or some other elevational line. The first course of siding is backed by a backer strip to provide it with the same vertical alignment as the overlying courses.

Various grades of beveled wood siding are available, depending on the presence of knots and other defects and on whether the siding is made of heartwood. Because the siding is exposed to weather, a better grade is relatively more warp resistant.

Beveled wood siding is nailed to each stud through sheathing. Nails should be of galvanized steel (or stainless steel) so that they do not stain the siding upon corrosion. The siding is nailed near its bottom, and the nails must clear the top of the siding below by at least $\frac{1}{8}$ in. This allows for expansion and contraction. Thus, each siding course is held at the bottom by the nail and at the top by the overlying siding.

Providing a #15 (or #30) asphalt-saturated felt or an air-weather retarder between the sheathing and siding is recommended. The ends of siding are butt-jointed and must be staggered to avoid a continuous vertical joint, Figure 16.4. A joint should occur at a stud and is caulked. Caulking is applied to both butting ends before nailing the siding.

As an additional precaution against the entry of water, a 4-in.-wide strip of #15 (or #30) felt or air-weather retarder material is placed behind the vertical joint, as shown in Figure 16.4. The height of this strip is the same as the width of the siding. It is positioned so that it is completely covered by the siding.

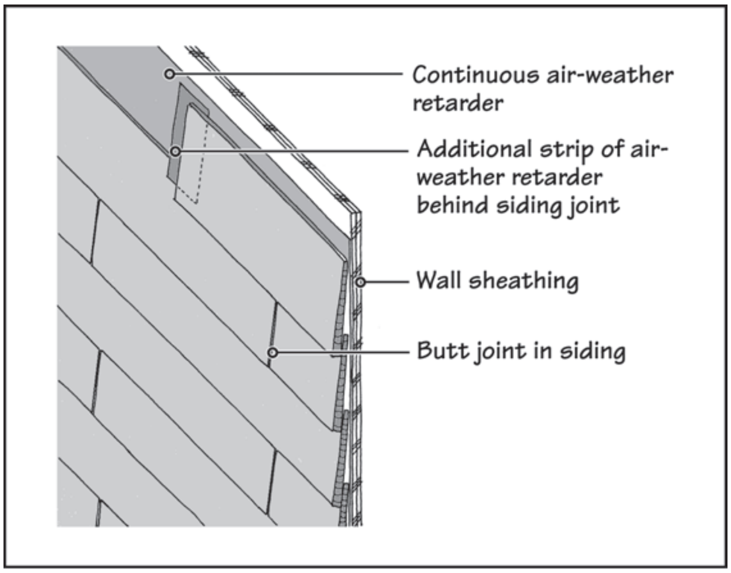

Continuous air-weather retarder
Additional strip of air-weather retarder behind siding joint
Wall sheathing
Butt joint in siding

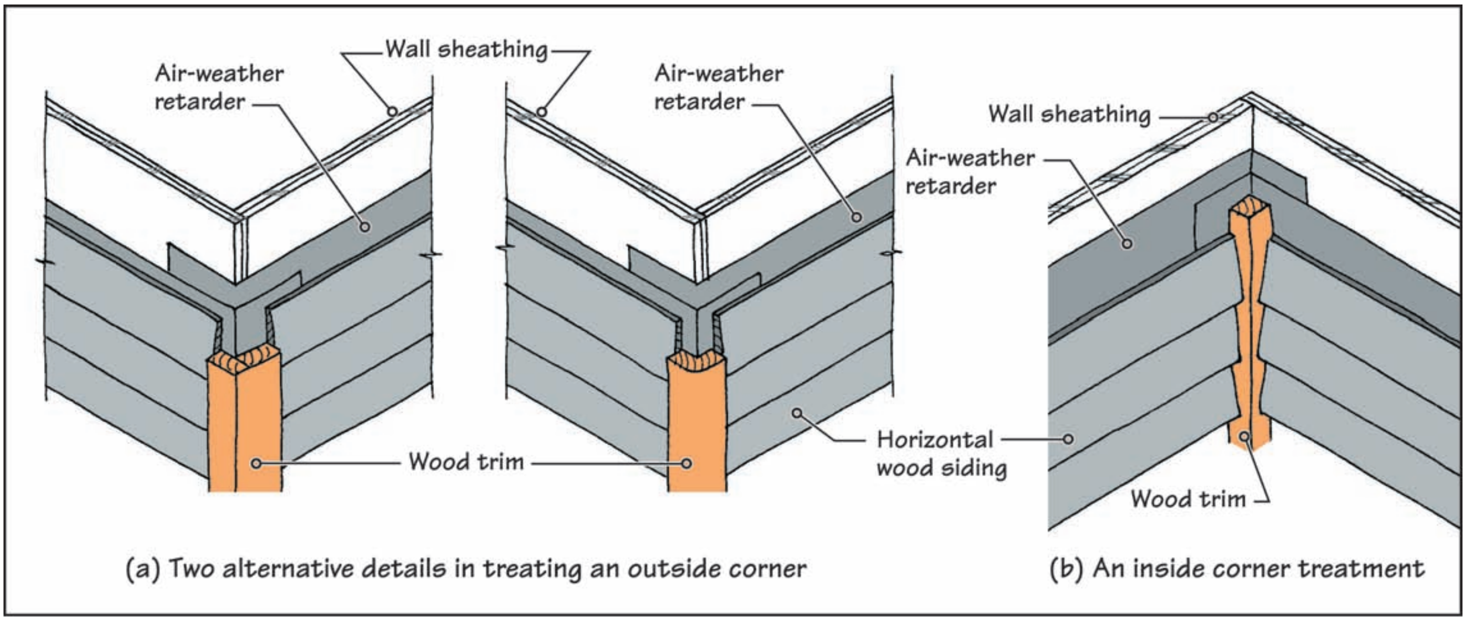
FIGURE 16.4 Use of an additional strip of air-weather retarder or asphalt-saturated felt behind a butt joint in siding.

Beveled wood siding should be back-primed before installation. At the corners and ends of walls, the siding butts against trim pieces, Figure 16.5. The trim is installed before the siding is applied. The vertical joints between the siding and trim are caulked in the same way as the butt-jointed ends of siding. Doors and windows should be installed before applying siding so that the siding butts against the trim surrounding the door or window frame, Figure 16.6.

HORIZONTAL SIDING WITH DRAINAGE LAYER

Figure 16.7 shows a method of applying horizontal siding with an air space between the siding and the sheathing. This space is created by nailing $1\frac{1}{2}$-in.-wide and almost $\frac{1}{2}$-in.-thick vertical wood or plywood strips over the studs. The space provides a drainage layer for any water that may infiltrate behind the siding, particularly under windy conditions. Detailing the bottom of the wall with a galvanized steel flashing is recommended, Figure 16.8.

The air space between the siding and sheathing also helps to dry the siding faster—an important consideration for wood siding, which is decay prone.



(a) Two alternative details in treating an outside corner

(b) An inside corner treatment

FIGURE 16.5 Typical corner treatment details for horizontal wood siding.

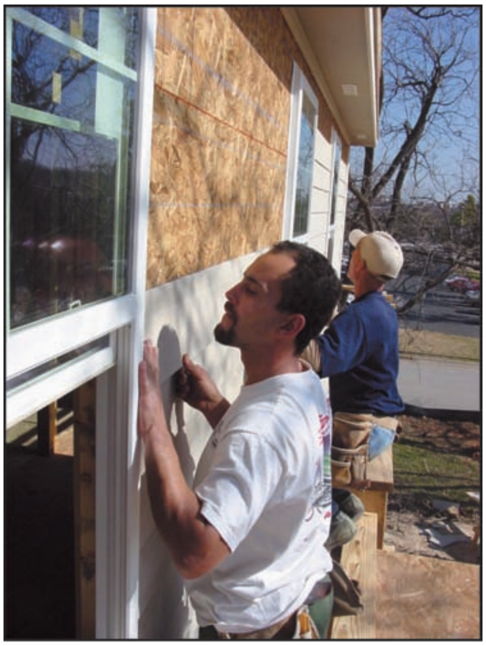
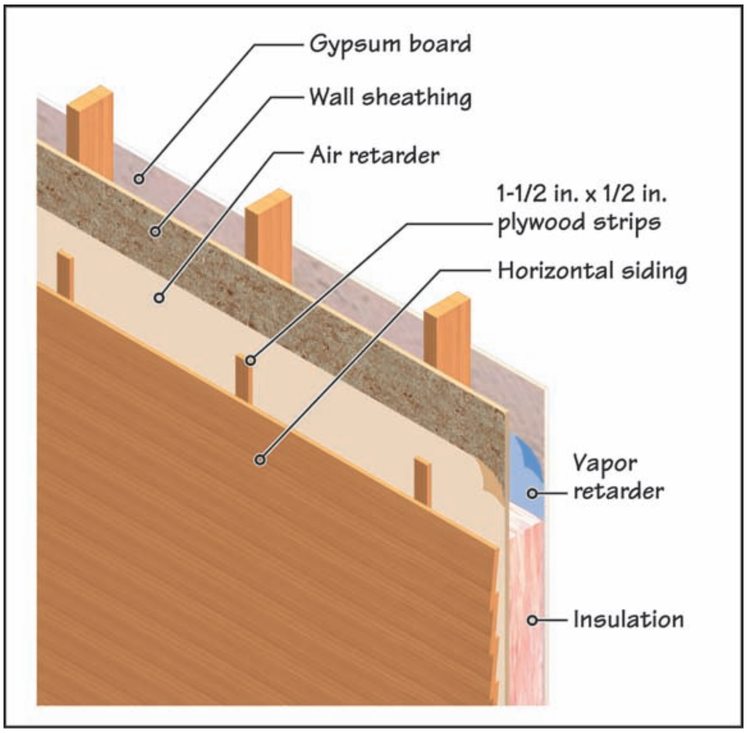


FIGURE 16.6 Installation of horizontal siding. Note that doors and windows are installed before siding is applied. In this building, an (outside) air retarder has not been installed because of the use of closed-cell, foamed-in-place insulation between stud cavities, which functions both as insulation and as air retarder; see Section 6.2.



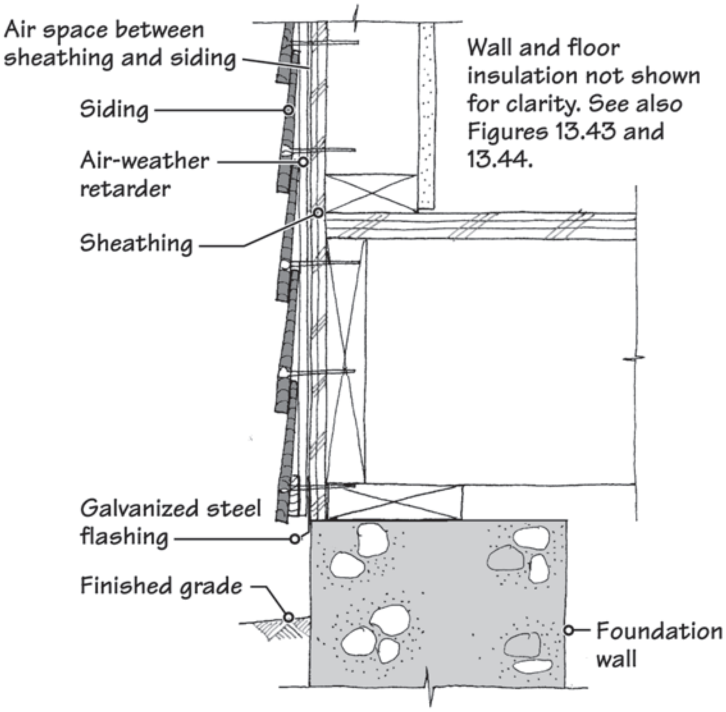
Gypsum board
Wall sheathing
Air retarder
1-1/2 in. x 1/2 in. plywood strips
Horizontal siding
Vapor retarder
Insulation

FIGURE 16.7 Horizontal wood siding with a drainage layer behind it.

PLYWOOD AND HARDBOARD SIDINGS

Plywood siding is more commonly used as vertical siding panels (described later), but strips of plywood for use as horizontal siding are available. Plywood siding strips are available as smooth-face veneers or rough-sawn face veneers to mimic rough-sawn lumber. Generally, smooth-face veneers are not plywood veneers but medium-density or high-density wood overlays.

Hardboard is made from wood chips bonded under heat and pressure to produce a high-density material. It is available in panels for vertical application or in strips for horizontal application. Hardboard siding manufacturers can provide slightly more complex profiles than wood siding, Figure 16.9. The method of application is similar to that described for beveled wood siding.



Air space between sheathing and siding
Siding
Air-weather retarder
Sheathing
Wall and floor insulation not shown for clarity. See also Figures 13.43 and 13.44.
Galvanized steel flashing
Finished grade
Foundation wall

FIGURE 16.8 Section through a wall with a drainage space behind the siding.

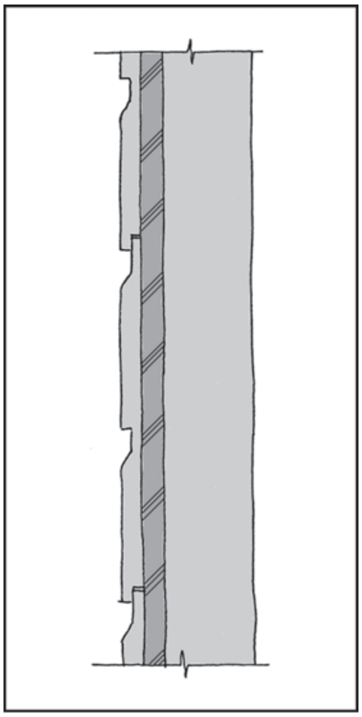


FIGURE 16.9 A commonly used hardboard horizontal siding profile.

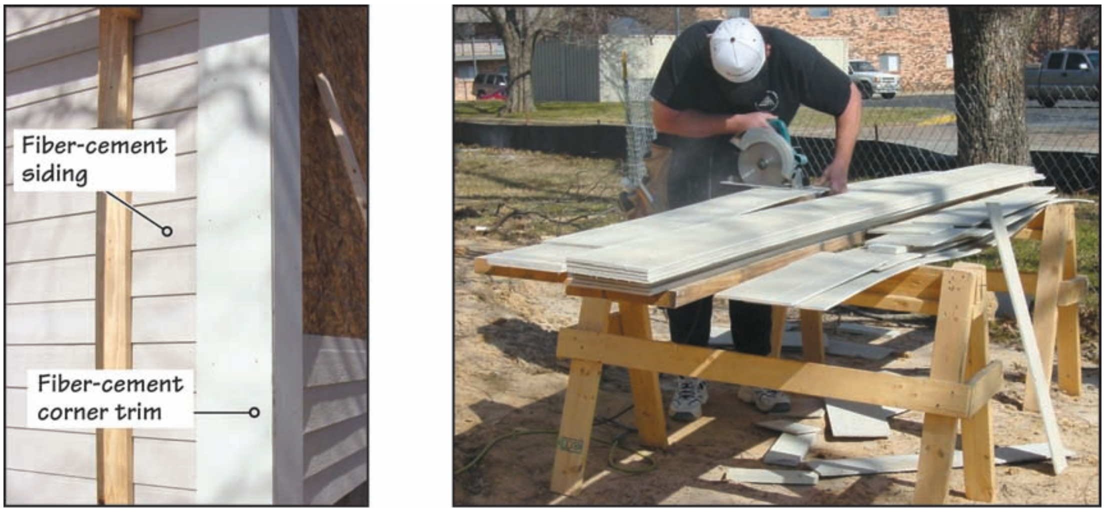


FIGURE 16.10 **(a)** Manufacturers of fiber-cement sidings provide trim materials to match their sidings. **(b)** Site cutting of fiber-cement siding.

FIBER-CEMENT SIDING

Fiber-cement siding is made from Portland cement, sand, and wood fibers. It is noncombustible and is not prone to decay like wood, plywood, or hardboard. Horizontal siding material is almost rectangular in profile (not beveled). It is available in 6-in. to 12-in. widths and is nearly $\frac{3}{8}$ in. thick.

Manufacturers generally recommend an overlap of $1\frac{1}{4}$ in. and provide trims for use at corners and around openings to match the siding, Figure 16.10. The cutting of fiber-cement boards and siding produces cement dust. The use of a dust mask is recommended during cutting.

VINYL SIDING

Vinyl siding is another commonly used cladding material for WLF buildings. It is molded from polyvinyl chloride (PVC), thermoplastic polyolefin (TPO), or polypropylene, often formed to look like wood siding. It is available in lap, shingle, and board-and-batten patterns. It is assembled using siding panels, soffits, various shapes of extruded trim, and accessories and is attached with corrosion-resistant nails. The material can be easily cut with a saw.

Vinyl siding is durable and water resistant when properly detailed. It can be cleaned with water and/or a mild detergent and does not require painting. Because vinyl tends to expand and contract substantially with changes in temperature, it is critical that it be properly installed to accommodate dimensional changes. Like wood siding, vinyl siding is also combustible.

16.3 VERTICAL SIDINGS

Wood boards can be used as vertical siding, Figure 16.11(a). The most commonly used vertical siding, however, is either plywood or hardboard panels. The panels are available in 4-ft width and heights of either 8 ft or 9 ft. The panels can be used either over wall sheathing or directly over the studs. If they are used directly over the studs, the span rating of siding panels should not be exceeded (see Figure 14.30).

Several vertical plywood or hardboard siding varieties have vertical grooves to mimic wood siding boards. A few of the several patterns available are shown in Figures 16.11(b) to (d). Vertical joints between panels are shiplapped. Horizontal joints require galvanized steel, aluminum, or stainless steel Z-flashing, Figure 16.11(e).

16.4 FINISHING THE EAVES, RAKES, AND RIDGE

The eave is the horizontal edge of the low side of a sloping roof. A hip roof has eaves on all four sides. A gable roof has eaves on two opposite sides. The sloping sides of a gable roof are referred to as *rakes* (Figure 15.25).

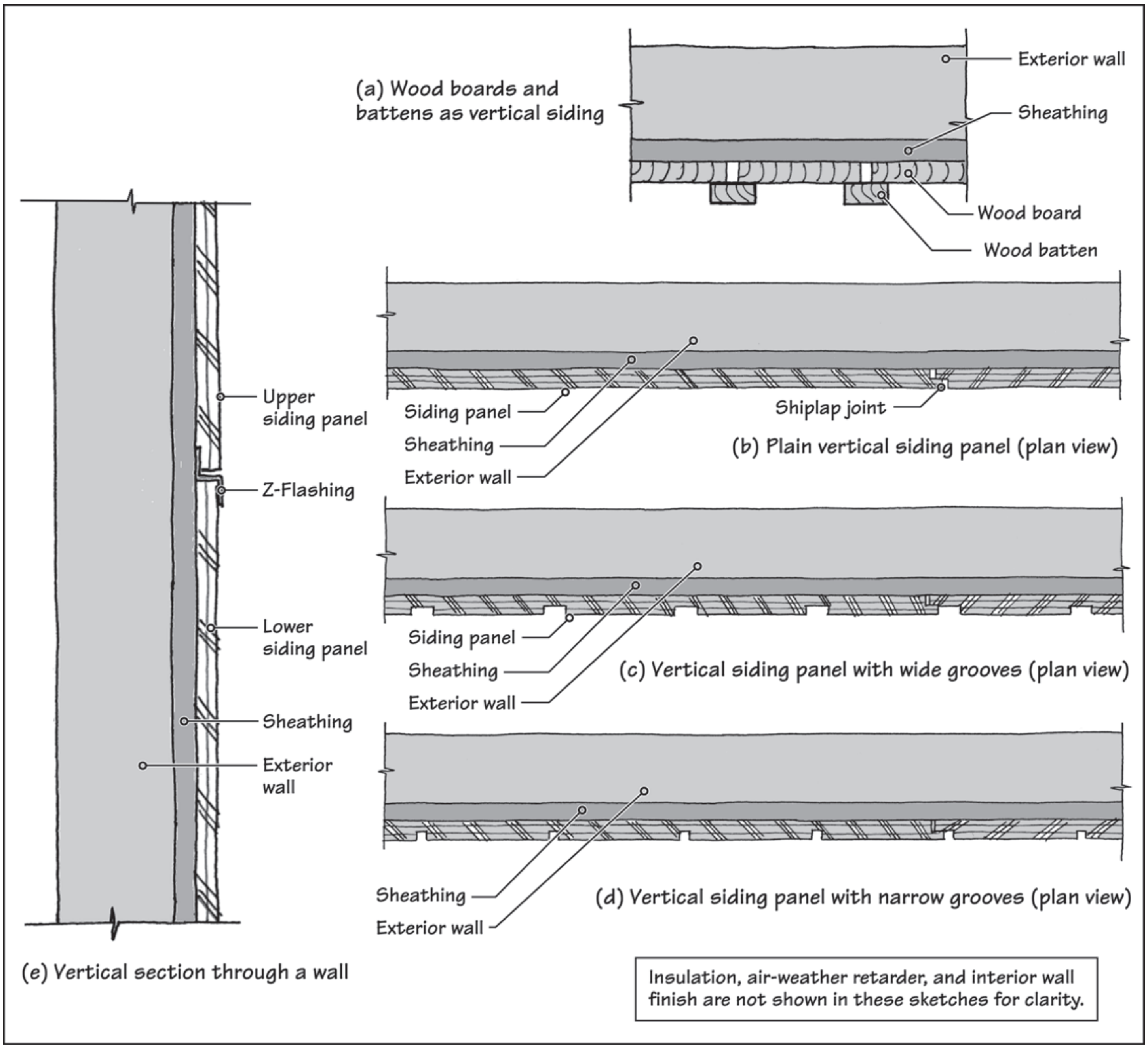

(a) Wood boards and battens as vertical siding
Exterior wall
Sheathing
Wood board
Wood batten
Upper siding panel
Z-Flashing
Lower siding panel
Sheathing
Exterior wall
Siding panel
Sheathing
Exterior wall
Shiplap joint
(b) Plain vertical siding panel (plan view)
Siding panel
Sheathing
Exterior wall
(c) Vertical siding panel with wide grooves (plan view)
Sheathing
Exterior wall
(d) Vertical siding panel with narrow grooves (plan view)
(e) Vertical section through a wall
Insulation, air-weather retarder, and interior wall finish are not shown in these sketches for clarity.

FIGURE 16.11 Vertical plywood or hardboard siding details.

The eave may be almost flush with the underlying wall or project over it. A projecting eave protects the junction between the wall and the roof from rain penetration and is the one more commonly used. The projection may be wide (2 to 3 ft) or narrow (a few inches) and may be finished with a horizontal soffit, Figure 16.12.

If the slope of the roof is large, an eave with a horizontal soffit cannot project too far beyond the wall, or the bottom of the soffit will interfere with the door or window head, Figure 16.13. A sloping soffit, Figure 16.14, does not have this limitation. A sloping soffit has another advantage over a horizontal soffit in that the transition from rake to eave is seamless. With a horizontal soffit, the transition requires additional detailing, Figure 16.15.

RIDGE VENTILATION

In Chapter 6 (Section 6.9), the importance of attic ventilation was discussed. As stated there, attic ventilation consists of intake and exhaust ventilation in the roof. Although intake ventilation is provided through soffit vents, exhaust ventilation can be provided in many ways (Figure 6.18).

One of the means of providing exhaust ventilation is to install a continuous ridge ventilator. Several proprietary ridge ventilators are available that can be installed over felt underlayment and covered over by roof shingles. The sheathing at the ridge is set back from the ridge board (by 1 to 2 in. on either side) to provide a clear space between rafters for ventilation, Figure 16.16.

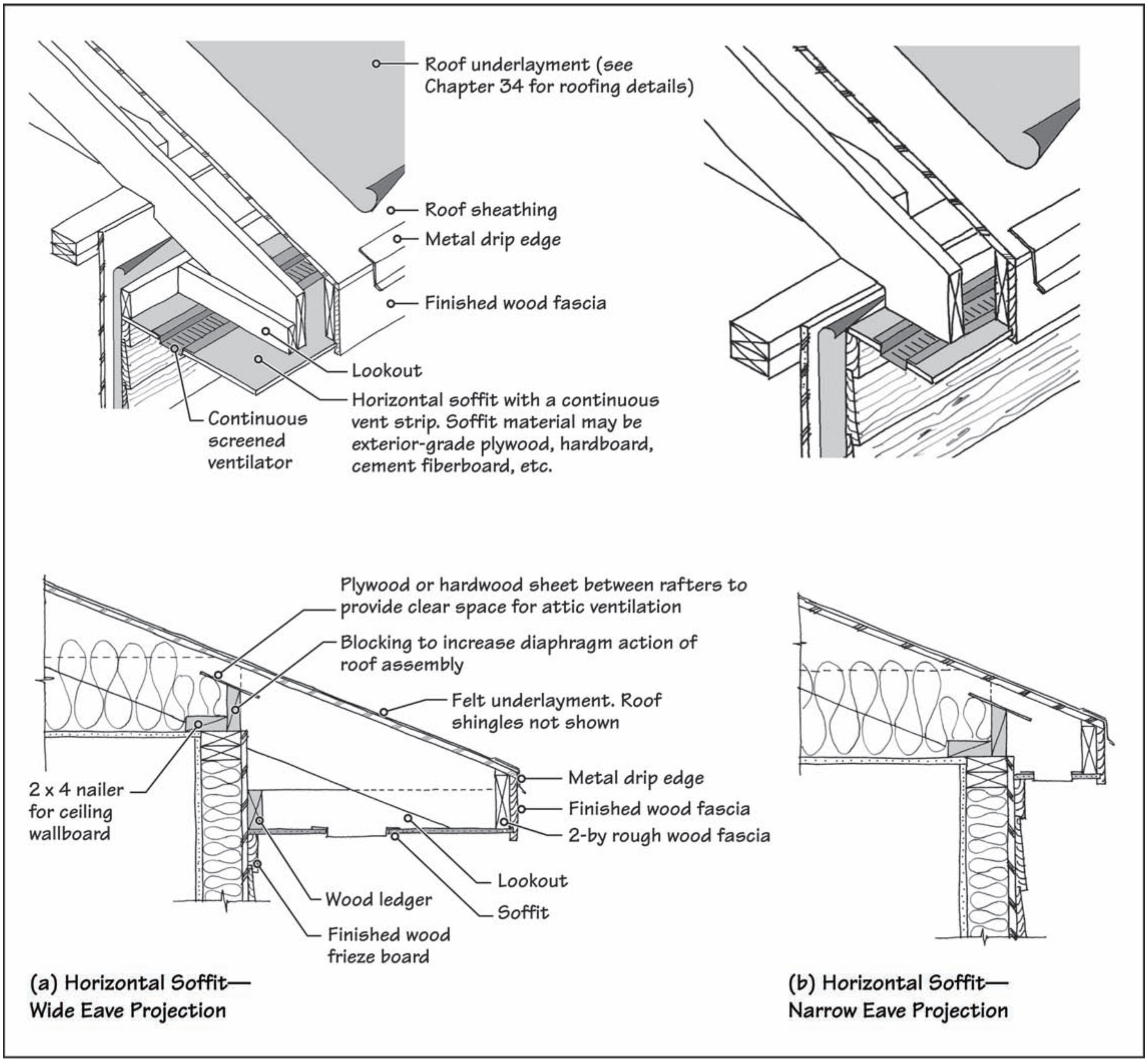

Roof underlayment (see Chapter 34 for roofing details)
Roof sheathing
Metal drip edge
Finished wood fascia
Lookout
Horizontal soffit with a continuous vent strip. Soffit material may be exterior-grade plywood, hardboard, cement fiberboard, etc.
Continuous screened ventilator
Plywood or hardwood sheet between rafters to provide clear space for attic ventilation
Blocking to increase diaphragm action of roof assembly
Felt underlayment. Roof shingles not shown
2 x 4 nailer for ceiling wallboard
Metal drip edge
Finished wood fascia
2-by rough wood fascia
Lookout
Wood ledger
Soffit
Finished wood frieze board
(a) Horizontal Soffit— Wide Eave Projection
(b) Horizontal Soffit— Narrow Eave Projection

FIGURE 16.12 Details of wide and narrow eave projections.

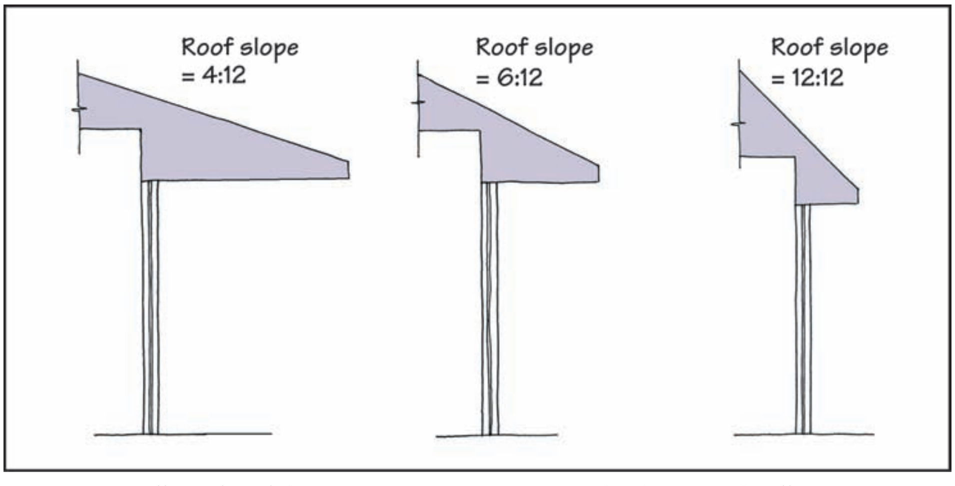

Roof slope = 4:12
Roof slope = 6:12
Roof slope = 12:12

FIGURE 16.13 Effect of roof slope on an eave projection with a horizontal soffit.

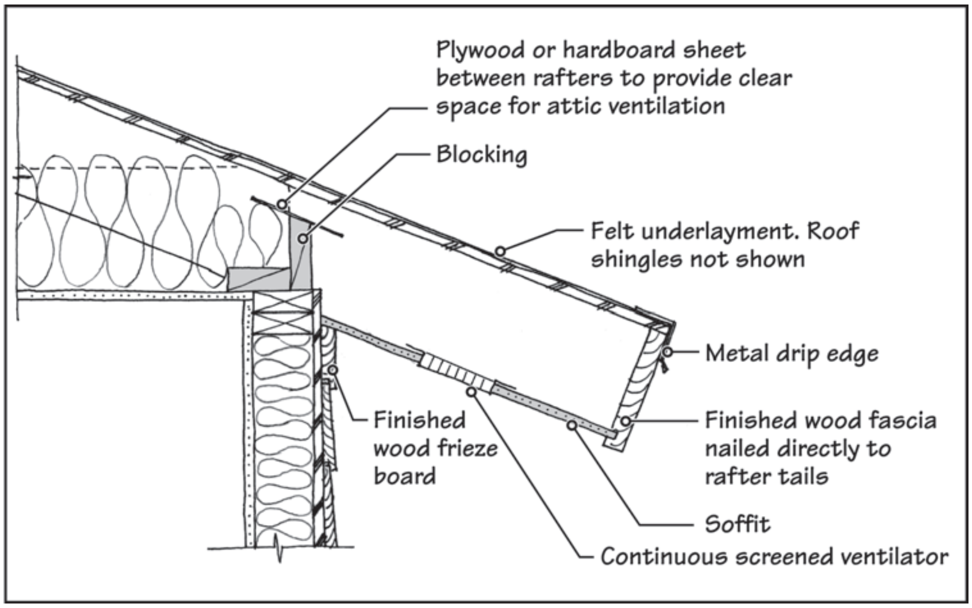

Plywood or hardboard sheet between rafters to provide clear space for attic ventilation
Blocking
Felt underlayment. Roof shingles not shown
Metal drip edge
Finished wood fascia nailed directly to rafter tails
Soffit
Continuous screened ventilator
Finished wood frieze board

FIGURE 16.14 Details of an eave projection with a sloping soffit.

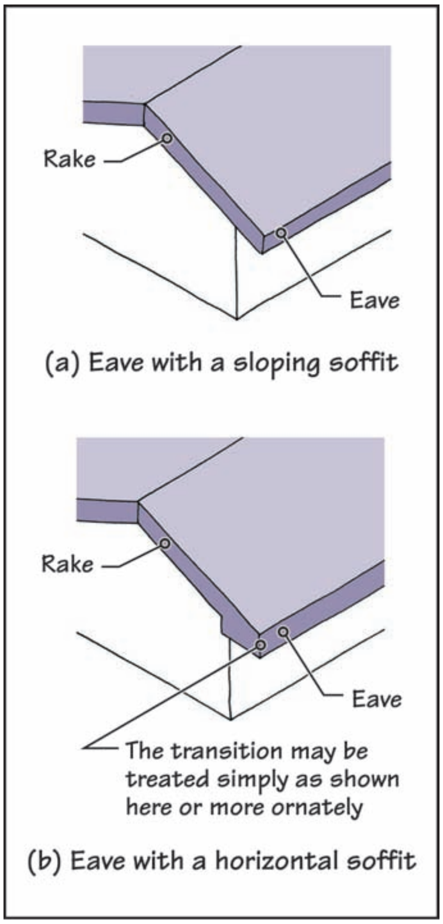

Rake
Eave
(a) Eave with a sloping soffit
Rake
Eave
The transition may be treated simply as shown here or more ornately
(b) Eave with a horizontal soffit

FIGURE 16.15 Eave-rake transitions.

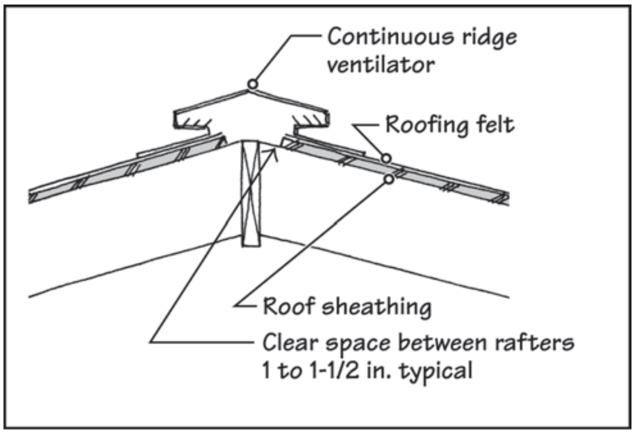

Continuous ridge ventilator
Roofing felt
Roof sheathing
Clear space between rafters 1 to 1-1/2 in. typical

FIGURE 16.16 One of the several ways of detailing for ridge ventilation.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. Horizontal beveled wood siding is generally made by slicing a
   - **a.** solid lumber piece.
   - **b.** LVL member.
   - **c.** glulam member.
   - **d.** OSB member.
   - **e.** plywood member.
2. Horizontal siding is provided on
   - **a.** the walls of a wood light-frame building.
   - **b.** the eave of a wood light-frame building.
   - **c.** the rake of a wood light-frame building.
   - **d.** the roof of a wood light-frame building.
3. Horizontal wood siding material is generally finished smooth on the front and back faces.
   - **a.** True
   - **b.** False
4. Each course of beveled horizontal wood siding is nailed to the wall through
   - **a.** one line of nails near the top of the siding.
   - **b.** one line of nails near the bottom of the siding.
   - **c.** one line of nails in the center of the siding.
   - **d.** two lines of nails, one at the bottom and one at the top of the siding.
5. Vertical joints between adjacent horizontal siding boards are generally
   - **a.** lapped $\frac{1}{2}$ in.
   - **b.** lapped at least 1 in.
   - **c.** lapped at least $1\frac{1}{2}$ in.
   - **d.** lapped at least 2 in.
   - **e.** none of the above.
6. To produce a drainage layer with horizontal siding, we generally use
   - **a.** 2-in.-wide horizontal strips nailed to sheathing.
   - **b.** $1\frac{1}{2}$-in.-wide horizontal strips nailed to sheathing.
   - **c.** 2-in.-wide horizontal strips nailed to studs before installing sheathing.
   - **d.** $1\frac{1}{2}$-in.-wide horizontal strips nailed to studs before installing sheathing.
   - **e.** none of the above.
7. Fiber-cement siding is
   - **a.** noncombustible but prone to fungal decay.
   - **b.** combustible and prone to fungal decay.
   - **c.** noncombustible and not prone to fungal decay.
   - **d.** none of the above.
8. Vertical siding for a wood light-frame building is generally made from small strips of plywood.
   - **a.** True
   - **b.** False
9. An eave is generally horizontal and the rake is inclined.
   - **a.** True
   - **b.** False
10. The transition from a projecting eave to a rake needs special detailing when the eave is provided with
    - **a.** a horizontal soffit.
    - **b.** a sloping soffit.
    - **c.** no soffit.

16.5 GYPSUM BOARD

Gypsum board is the most commonly used interior wall and ceiling finish in virtually all types of buildings. It provides a strong, fire-protective cover over framing members and can be finished with paint, wallpaper, wood paneling, and so on. It is more economical and much easier to install and finish than the lath-and-plaster alternative that preceded it. Additionally, being a dry form of construction, it leaves less construction mess than lath and plaster.

Gypsum board is known by several names that are used synonymously—*drywall, wallboard, gypsum wallboard* (GWB), and *plasterboard*. The term *sheetrock* is not a generic name but is proprietary to a gypsum board manufacturer.

WHY GYPSUM IS A WONDROUS MATERIAL WITH RESPECT TO FIRE

Gypsum is a rocklike mineral found extensively on the earth's surface. Its chemical name is calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), which indicates that every molecule of gypsum contains two molecules of water (H_2O) chemically combined with one molecule of calcium sulfate ($CaSO_4$). The consequence of gypsum's chemical formulation is that 100 lb of gypsum rock contains 21 lb of water, that is, 21% of gypsum rock is water. (The prefix *di* in dihydrate means "two".)

It is the water contained in gypsum that gives it its fire-protective property. Under the action of heat, the water in gypsum converts to steam. Steam not only helps to absorb the heat, but also provides a cooling effect. Because the temperature of water cannot exceed its boiling point (212°F), regardless of how long the fire acts on it, the temperature of gypsum rock cannot equal that of fire unless all the water in gypsum has been converted to steam. Once all the water has turned into steam, gypsum begins to disintegrate under the effect of fire. Therefore, the presence of water in gypsum slows the disintegration process.

The temperature gradient of the wall after 2-h fire exposure, when a 6-in.-thick solid gypsum wall is exposed to fire in the standard test and the temperature of the wall at various points within the wall, is shown in Figure 16.17. Observe that after 2 h, the temperature of the unexposed face of the wall is only 130°F, and the temperature of the wall 2 in. away from the fire side is the boiling point of water—212°F.

ANATOMY AND SIZES OF GYPSUM BOARD PANELS

Gypsum board consists of a gypsum core, which is sandwiched between specially treated paper faces, Figure 16.18. The paper adds strength to the board and provides a smooth surface for finishing and painting.

The most commonly used size of gypsum board is a 4-ft × 8-ft panel. Some of the other commonly used sizes are 4 ft × 9 ft, 4 ft × 10 ft, and 4 ft × 12 ft. Boards of width 4 ft 6 in. are also available and are used horizontally on walls in rooms with 9-ft-high ceilings. Longer boards are more cumbersome to install. They are heavier to carry and more difficult to

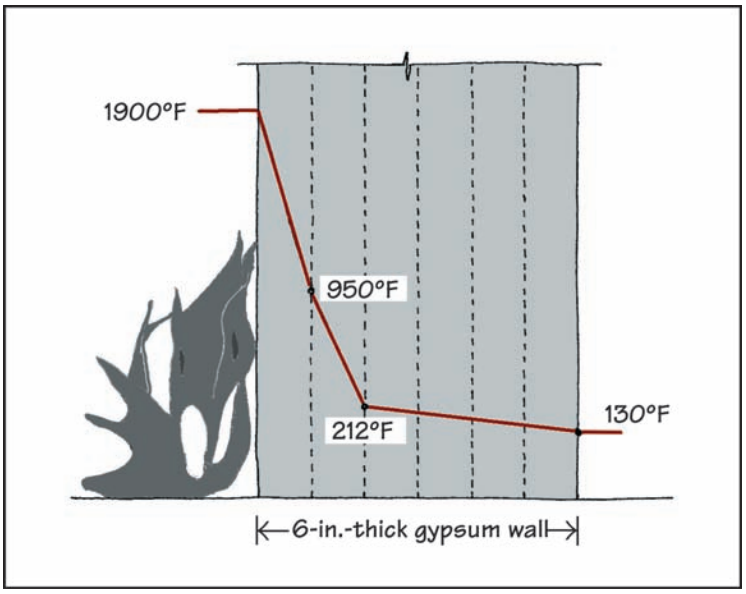


FIGURE 16.17 Temperature gradient along a 6-in.-thick gypsum wall after 2-h exposure to fire under the ASTM E119 test—the test used to determine the fire rating of assemblies (see the Expand Your Knowledge section in Chapter 7).

NOTE

Plaster of Paris

When gypsum is heated to remove 75% of its water, the resulting product is calcium sulfate hemihydrate (*hemi* means "half"), referred to as *plaster of Paris*. The chemical notation of plaster of paris is $CaSO_4 \cdot \frac{1}{2} H_2O$. (Ca is the symbol for calcium and SO_4 is the symbol for sulfate, so $CaSO_4$ stands for calcium sulfate.) When water is added to plaster of paris, it returns to its original hard, rocklike form—gypsum—containing calcium sulfate and two molecules of water.

Because plaster of paris reverts to gypsum with the addition of water and its subsequent setting, plaster of paris expands on setting. This is unlike Portland cement, which shrinks on setting due to the evaporation of water. Thus, plaster of paris is used for casting in molds because it accurately assumes the shape of the mold.

If water is completely removed from gypsum, the resulting product, which is pure calcium sulfate, is called *anhydrite*. Anhydrite has a longer setting time than plaster of paris and is marketed as Keene's cement, used as a finish coat in interior plaster.

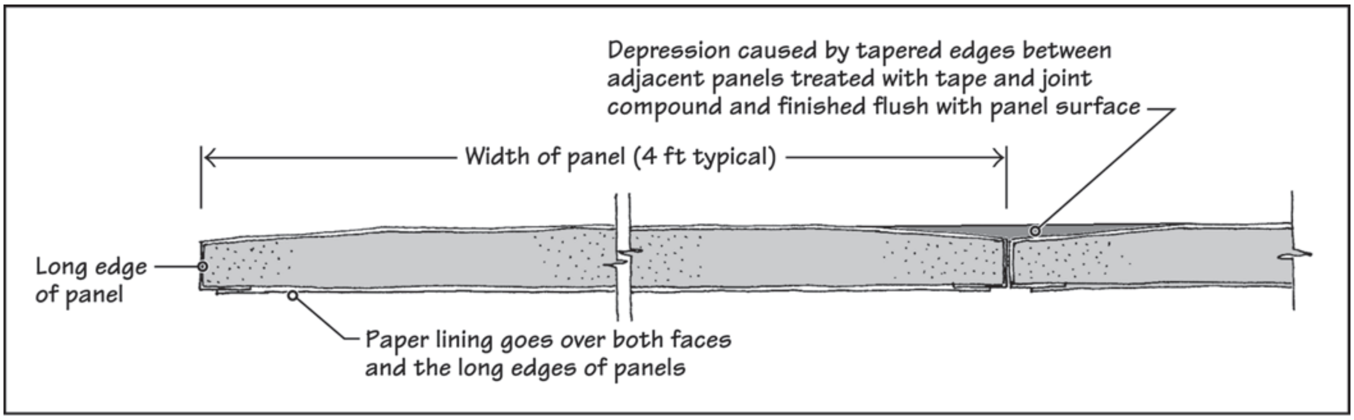

Depression caused by tapered edges between adjacent panels treated with tape and joint compound and finished flush with panel surface
Width of panel (4 ft typical)
Long edge of panel
Paper lining goes over both faces and the long edges of panels

FIGURE 16.18 Section through a gypsum board panel.

maneuver in stair enclosures and other interior spaces. However, fewer joint seams in longer boards reduce cutting of boards and finishing of seams.

The most frequently used board thickness for residential buildings is $\frac{1}{2}$ in. For commercial buildings, the corresponding thickness is $\frac{5}{8}$ in. Other available thicknesses are $\frac{3}{8}$ in. and $\frac{1}{4}$ in.

The long edges of a gypsum board are tapered, as shown in Figure 16.18. The taper allows the joints to be taped over and filled with a joint compound so that a finished wall or ceiling surface appears jointless. The boards that do not require finishing (e.g., prefinished boards and gypsum sheathing panels) have square (nontapered) long edges.

The manufacturing process of gypsum boards yields an endlessly long board wrapped with paper, which is cut to the desired lengths. Therefore, the short (4-ft-wide) edges where the cut is made do not have paper wrapping and have smooth, square edges (not tapered).

TYPES OF GYPSUM BOARD PANELS

Several different types of gypsum board panels, with different properties, are available. The more commonly used types are as follows:

- *Type R (regular) boards:* Type R boards are the standard boards, typically used in $\frac{1}{2}$-in. thickness.
- *Type X boards:* Type X boards are more fire resistive than Type R boards. The core in Type X boards contains noncombustible fibers (e.g., fiberglass) mixed with gypsum. The fibers provide greater strength so that the boards, if subjected to fire, maintain their structural integrity for a longer time than Type R boards.

  By definition, a Type X gypsum board, when used in $\frac{5}{8}$-in. thickness on both sides of a wood or metal stud, gives a minimum 1-h fire rating. A $\frac{5}{8}$-in.-thick board that does not give a 1-h fire rating is not a Type X board. A $\frac{1}{2}$-in.-thick Type X panel gives a 45-min fire rating. Manufacturers call their Type X boards by different brand names, such as Firecode Core (U.S. Gypsum Company), Firebloc (American Gypsum Company), Fire-shield (National Gypsum Company), and so on, Figure 16.19.
- *Mold-and-moisture-resistant (MMR) boards:* These boards employ several different proprietary technologies to resist mold and moisture absorption. Some combine a moisture-resistant core with paper that is treated on one side to be more resistant to mold.

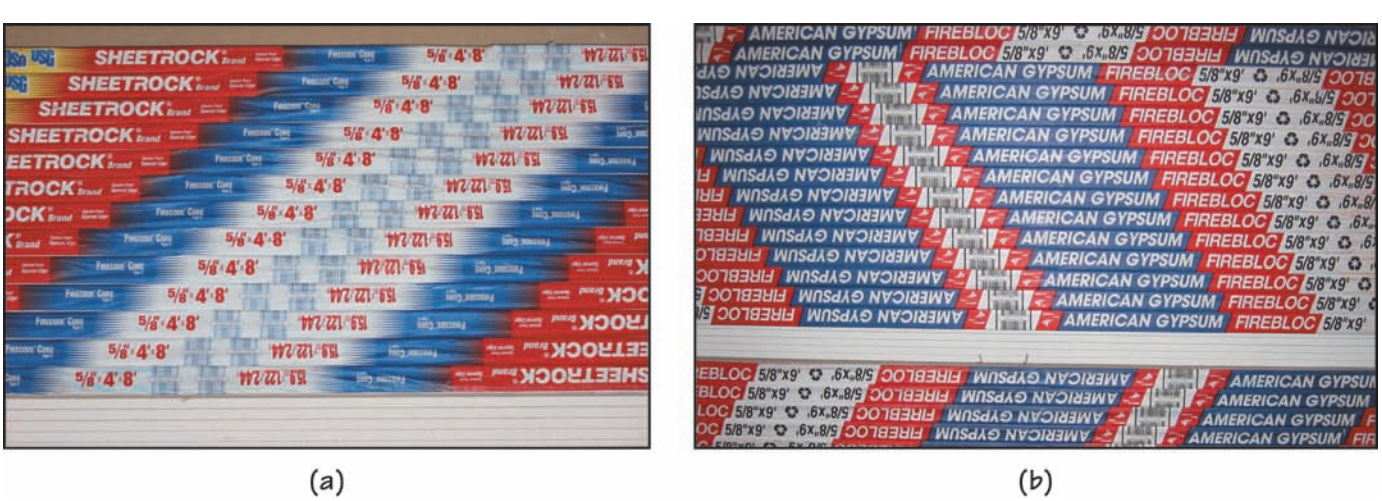

SHEETROCK
5/8 4'8'
AMERICAN GYPSUM
FIREBLOC 5/8"x9'
(a)
(b)

FIGURE 16.19 Type X gypsum panels: **(a)** called Firecode by U.S. Gypsum Company and **(b)** called Firebloc by American Gypsum Company.

Another uses a moisture-resistant core sandwiched between glass mats on both faces. Mold resistance is determined by an ASTM test that rates panels on a scale from 1 to 10, 1 being the least resistant and 10 being the most resistant panel. The test is conducted over a four-week period, giving only a short-term rating.

MMR boards are specified for bathroom walls and ceilings and for any other areas where greater resistance to mold is required, such as the walls and ceilings of hospitals and nursing homes.

- *Flexible boards:* These boards are more flexible than other gypsum boards and are meant for use on curved walls or ceilings. They are $\frac{1}{4}$ in. thick and have heavier paper facing to resist cracking. They are generally used in two layers or more to give the required gypsum thickness.
- *High-impact boards:* These are boards that have a thick fiberglass mesh embedded in the core near the back to provide greater impact and penetration strength compared with other boards. They are available as Type R or X.
- *Prefinished boards:* These boards are covered on one face with vinyl instead of paper and do not require any finishing (tape and bed, paint, or wallpaper). Generally, both long and short panel edges are square (not tapered). Manufacturers provide special nails to match the color and texture of the finish in addition to joint-cover accessories. The vapor impermeability of vinyl covering should be taken into account before specifying the use of prefinished boards in warm, humid climates.
- *Gypsum wall sheathing boards:* Although gypsum wall sheathing in wood frame buildings is used much less since the introduction of OSB boards, it is used in situations where the fire rating of the exterior walls is a concern. Gypsum wall sheathing boards have a specially treated core and water-resistant paper facings. The long edges of boards are profiled to shed water, Figure 16.20. The boards are available as Type R or X. Paper-faced gypsum sheathing has been largely replaced by fiberglass-mat-faced gypsum sheathing because of the delamination of paper when it gets wet and the paper being a food source for the growth of mold.

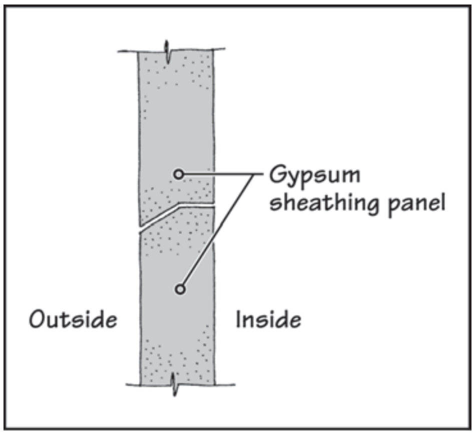


FIGURE 16.20 Vertical cross section through horizontally applied, paper-faced gypsum sheathing panels.

NOTE

Portland Cement Boards

While MMR boards are specified for bathroom walls and ceilings because of the greater relative humidity in bathrooms, they cannot be used on surfaces that receive direct water, such as the glazed ceramic tile walls surrounding a shower or bathtub. On such surfaces, the tiles should not be backed by gypsum boards, but by Portland cement boards because of their greater water resistance. A Portland cement board is made of Portland cement, sand, and glass fibers or cellulose fibers. It is stronger than gypsum board of the same thickness but more difficult to install. Portland cement boards are also used as underlayment for ceramic tile flooring.

LIMITATIONS OF GYPSUM BOARDS

Gypsum is a water-soluble material. Therefore, it is basically an interior-use material. Gypsum boards (including MMR boards) are not recommended for use in locations with direct exposure to water or continuous interior high humidity, such as in swimming pool enclosures, steam rooms, or gang shower rooms. However, gypsum boards are available for use in protected exterior locations such as for eave soffits (soffit panels) or as wall sheathing.

16.6 INSTALLING AND FINISHING INTERIOR DRYWALL

Gypsum boards (drywall panels) are fastened to framing members using drywall nails or screws. Screw application is preferred because screws eliminate nail popping caused by wood shrinkage, provide better holding power, and do not cause impact damage on the panels. However, modern pneumatic nailers make nailing gypsum boards much faster than fastening with screws. On metal studs, only screws can be used. The nail or screw heads are slightly depressed into the panel surface so that they can be filled with joint compound and leveled with the panel surface.

After the drywall panels have been secured to the walls and ceilings, their surfaces are prepared to receive the paint. Surface preparation is referred to as *tape and bed* in the drywall trade, which includes reinforcing the joints between drywall panels with a tape, covering fastener depressions with joint compound, and reinforcing the interior corners (wall-to-wall and wall-to-ceiling), and exterior wall-to-wall corners.

The joints between drywall panels are reinforced by taping the joints with a 2-in.-wide paper tape, Figure 16.21. The tape is embedded within the joint compound. Embedding the tape is a three-step process: (i) spreading a thin layer of joint compound over the joint using a taping knife (typically 5 in. wide), (ii) applying the tape over the joint compound by pressing it into the wet layer of joint compound using a taping knife, and (iii) spreading a thin layer of joint compound over the tape, Figure 16.22. The term "bed" in "tape and bed" refers to the embedment of the tape between two coats of joint compound.

The joint compound (also referred to as *mud* in the drywall trade) has a plaster-type consistency and is available in pails or cartons in a ready-to-use

FIGURE 16.21 Paper tape used for reinforcing the joints between drywall panels.

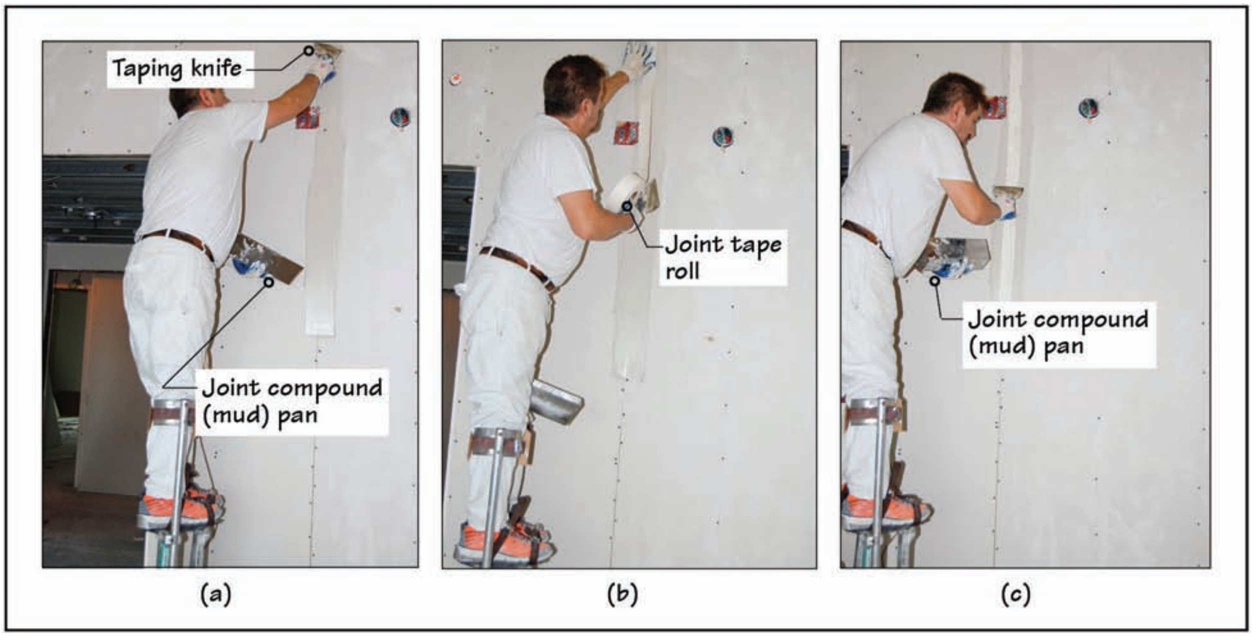


FIGURE 16.22 Taping the joints between gypsum board panels (butt joints as well as tapered joints) is a three-step process, which includes: (**a**) applying a thin coat of joint compound over the joint with a taping knife, (**b**) lightly pressing the tape over the wet compound with fingers, and (**c**) applying an additional coat of joint compound over the tape with the taping knife so that the tape is fully embedded within the coats.

formulation. Drywall finishers use a pan to hold the mud in one hand and a knife in the other to apply the mud as needed, as shown in Figure 16.22. On large jobs, the drywall contractors use barrel-type taping tool that contains paper tape mounted on two rollers, one at each end of the barrel. The barrel contains the joint compound. The taping tool, referred to as the *bazooka* (because of its resemblance with the anti-tank rocket launcher gun), increases workers' productivity by replacing the three-step process previously described into a one-step process. It also obviates the need for a mud pan and taping knife, Figure 16.23.

Taping and bedding of the panel joints is followed by additional and wider overcoats of joint compound. After the previous coat has dried, it is feathered smooth with a sander, and another coat of joint compound and sanding is done until the joint is ready to receive the paint. The same process is repeated for the joint compound applied over the lines of fasteners.

Inside corners of rooms are taped with paper tape, Figure 16.24. The paper tape has a built-in crease, along which the tape is folded, as shown in Figure 16.21. The folded tape is embedded between two coats of joint compound and finished smooth in the same way as a flat joint.

The outside corners require L-shaped metal trims (called *corner beads*), which are fastened into the studs through the drywall panel. The trim is covered with three to four coats of joint compound, making sure that the previous coat has dried and sanded before applying the next

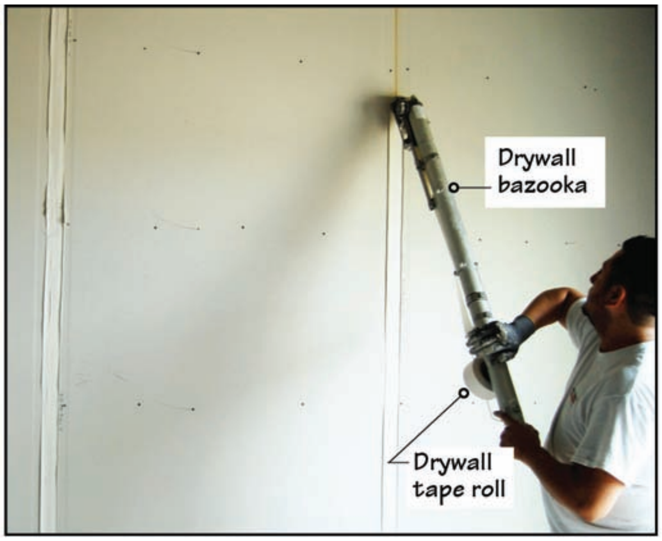


FIGURE 16.23 Drywall taping tool, called *bazooka*, integrates all three steps of tape and bed operation into one step, and is commonly used on large- and medium-size jobs.

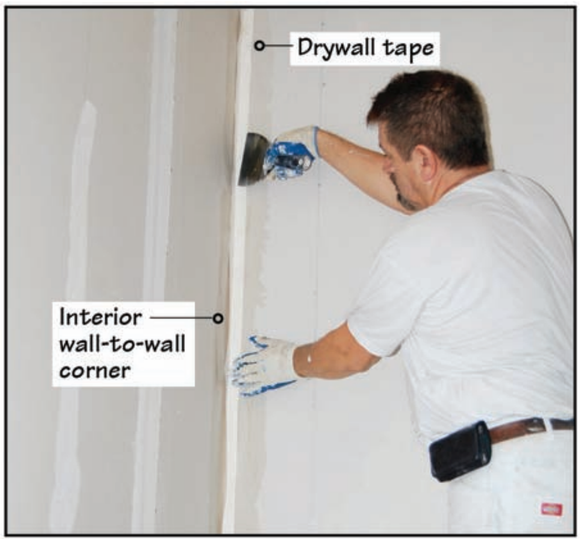


FIGURE 16.24 Reinforcing an interior wall-to-wall corner with paper tape; wall-to-ceiling corner reinforcement is similar.

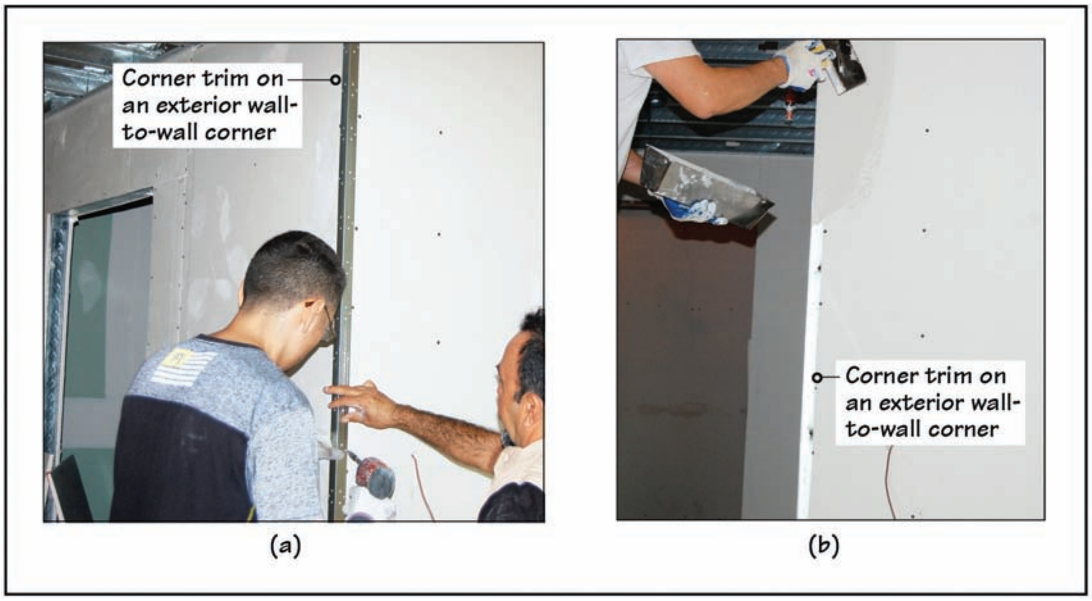

Corner trim on an exterior wall-to-wall corner
(a)
Corner trim on an exterior wall-to-wall corner
(b)

FIGURE 16.25 Reinforcement of an exterior wall-to-wall corner is done by: **(a)** fastening a metal trim, also called *corner bead*, on the corner and **(b)** covering the trim with several coats of joint compound and sanding the surface smooth.

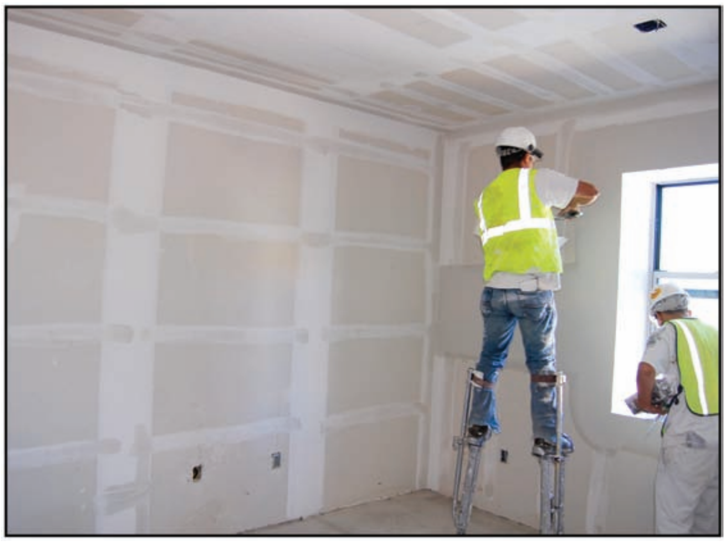


FIGURE 16.26 A drywall interior that is almost ready to receive the paint. The wider (vertical) coverage of the panels with joint compound is over the tapered panel joints and the narrower coverage is on the fastener lines at the butt joints between panels and the horizontal resilient channels behind the panels, typically installed at 24 in. on center. (For resilient channels, see Chapter 8.)

coat, and finally finishing flush with the surface of the boards, Figure 16.25. When all joints, fastener lines, and corners are finished and the interior is ready to receive the paint, it looks somewhat as shown in Figure 16.26.

Gypsum boards must be fastened to every framing member. On walls, Type R boards may be applied either horizontally or vertically. However, because Type X boards are used in fire-rated assemblies, they must be installed as per the instructions of the manufacturer of the rated assembly. Fastener spacing depends on the spacing between framing members and the required fire rating of the assembly, as described in Section 16.7.

MULTILAYER DRYWALL

Although one-layer application is the norm, sometimes two or more layers of drywall panels may be needed on one or both faces of the assembly to obtain a higher fire rating or higher sound insulation. In such an assembly, each layer may be nailed or screwed. The screw (or nail) size and spacing must be as per the assembly tested for fire rating or sound rating.

With prefinished boards, in which two-layer application is common, the base layer is fastened with nails or screws and the face layer is adhered to the base layer using manufacturer-provided adhesives. Temporary nailing is generally required on the edges of face panels to hold them in place until the adhesive has attained strength.

16.7 FIRE-RESISTANCE RATINGS OF WLF ASSEMBLIES

The fire-resistance rating of a WLF wall or ceiling-floor assembly depends on the type of drywall panels. Generally, one $\frac{5}{8}$-in.-thick Type X drywall panel on each side of a wood stud wall gives a 1-h fire-resistance rating. If two layers of the same drywall panels are used, a 2-h fire-resistance rating is obtained. Three such layers give a 3-h rating, Figure 16.27.

However, the fire-resistance rating also depends on the spacing of studs, the spacing and type of nails or screws, and whether or not wall cavities are insulated. Drywall manufacturers provide the fire-rating data for various assemblies in which their product can be used. Another standard source for this information is the *Fire Resistance Design Manual* published by the Gypsum Association, which is updated every few years. This publication gives the specifications and sketches of 1-h-, 2-h-, and 3-h-rated assemblies. These ratings have been established based on measurements in standard fire tests. Because the ratings are in integer hours, an assembly whose measured fire-resistance rating is 1 h 59 min is listed as a 1-h assembly. To be listed as a 2-h assembly, its fire rating must lie between 2 h and 2 h 59 min.

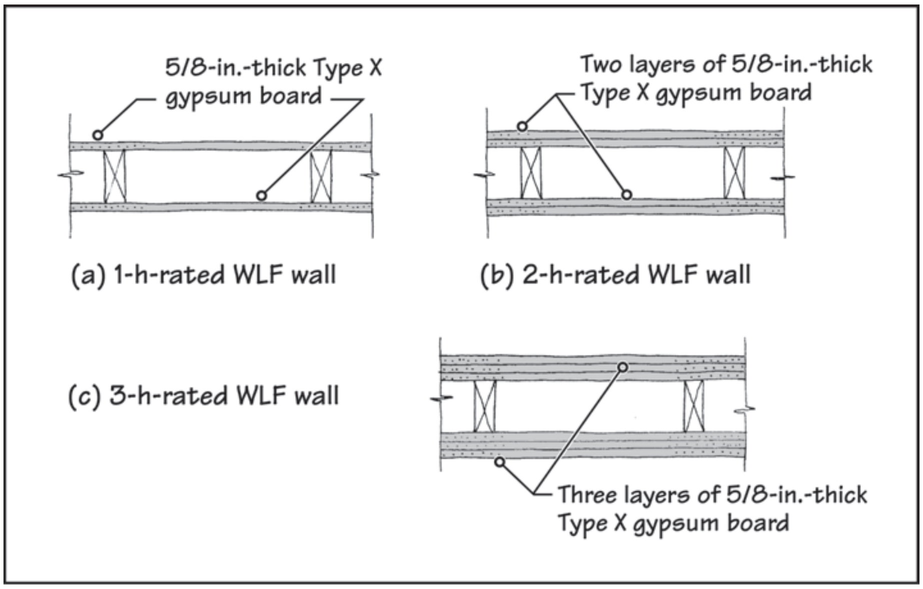

5/8-in.-thick Type X gypsum board
(a) 1-h-rated WLF wall
Two layers of 5/8-in.-thick Type X gypsum board
(b) 2-h-rated WLF wall
(c) 3-h-rated WLF wall
Three layers of 5/8-in.-thick Type X gypsum board

FIGURE 16.27 Fire-rated wood frame assemblies are generally obtained by using one or more layers of $\frac{5}{8}$-in.-thick Type X gypsum board. Although the type and thickness of gypsum board are the primary factors that determine the fire rating of a wood frame assembly, a few other factors are also important. These include the type and spacing of nails or screws, the spacing of framing members (studs or ceiling joists), the provision of insulation within framing members, and whether the panel is applied horizontally or vertically.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

11. Which of the following terms for gypsum board is proprietary to a manufacturer?
- **a.** *Wallboard*
- **b.** *Sheetrock*
- **c.** *Plasterboard*
- **d.** *Drywall*

12. Gypsum board is one of the best materials for fire protection because
- **a.** it is noncombustible.
- **b.** it is heat-treated during its manufacture.
- **c.** each molecule of gypsum contains two molecules of water that retard the progress of fire.
- **d.** each molecule of gypsum contains two molecules of carbon dioxide that retard the progress of fire.

13. The most commonly used size for gypsum boards is
- **a.** 4 ft × 8 ft.
- **b.** 4 ft × 8 ft 6 in.
- **c.** 4 ft 6 in. × 8 ft.
- **d.** 3 ft × 6 ft.
- **e.** 4 ft × 4 ft.

14. Of Types R and X gypsum board panels, both of the same thickness, Type R is more fire resistive.
- **a.** True
- **b.** False

15. One sheet of Type X gypsum board panel, $\frac{5}{8}$ in. thick, used on each side of a stud wall gives a fire rating of
- **a.** 30 min.
- **b.** 45 min.
- **c.** 60 min.
- **d.** 75 min.
- **e.** 90 min.

16. Moisture-resistant gypsum board panels are generally
- **a.** green in color.
- **b.** pink in color.
- **c.** white in color.
- **d.** yellow in color.
- **e.** gray in color.

17. Gypsum board panels used on curved walls are generally
- **a.** $\frac{5}{8}$ in. thick.
- **b.** $\frac{1}{2}$ in. thick.
- **c.** $\frac{3}{8}$ in. thick.
- **d.** $\frac{1}{4}$ in. thick.
- **e.** $\frac{1}{8}$ in. thick.

18. High-impact gypsum board panels generally have a
- **a.** steel lining at the back side.
- **b.** aluminum foil lining at the back side.
- **c.** fiberglass mesh at the back side.
- **d.** plastic sheet at the back side.
- **e.** none of the above.

19. Gypsum sheathing is generally used on the
- **a.** exterior side of an exterior stud wall.
- **b.** interior side of an exterior stud wall.
- **c.** exterior side of an exterior masonry wall.
- **d.** interior side of an exterior masonry wall.

20. It is better to install ceiling gypsum board panels before installing the wall panels in a room.
- **a.** True
- **b.** False

21. The most important reason for using more than one layer of gypsum board panels on one or both faces of a wall is to obtain a stronger wall assembly.
- **a.** True
- **b.** False

REVIEW QUESTIONS

1. List various exterior wall finishes used in wood light-frame buildings. Which of these finishes are unique to (wood or steel) light-frame buildings.
2. Draw a detail section at the foundation level through a wood light-frame building whose exterior wall is finished with beveled wood siding. Assume a crawl space under the ground floor.
3. List various types of sidings commonly used in buildings.
4. Explain why gypsum board is an excellent material for providing fire resistance in building assemblies.
5. Explain the difference between a Type R gypsum board and a Type X gypsum board.
6. What is an MMR gypsum board? Where would you specify it?
7. What are the important differences between Portland cement boards and gypsum boards?
8. Using a sketch and notes, explain how you will detail a 2-h fire-rated wood light-frame wall assembly.

CHAPTER 17

Structural Insulated Panel Construction

CHAPTER OUTLINE

17.1 Basics of the Structural Insulated Panel (SIP) System

17.2 SIP Wall Assemblies

17.3 SIP Floor Assemblies

17.4 SIP Roof Assemblies

17.5 Advantages and Limitations of SIPS

The structural insulated panel system of construction described in this chapter is an alternative to the conventional WLF system. It is a panelized system that reduces on-site construction time and allows the use of less skilled labor. Panelization, however, necessitates the use of hoisting equipment such as cranes, forklifts, booms, and so on during construction, Figure 17.1, whose use in WLF construction is generally limited.

Because insulation is part of the panels, the insulation subtrade is eliminated, which further increases construction efficiency. Several other advantages of the system, as well as its limitations, are described at the end of this chapter. Because the structural insulated panel is a relatively new system that is still evolving, its current market share is small compared with that of the well-established conventional WLF system that dominates the residential and light commercial construction market in the United States.

In addition to all structural insulated panel construction, structural insulated panels are used as wall and roofing panels in timber frame buildings (see the Expand Your Knowledge section in Chapter 15) and low-rise steel frame buildings.

17.1 BASICS OF THE STRUCTURAL INSULATED PANEL (SIP) SYSTEM

The structural insulated panel (SIP) system consists of panels of sandwich composition. Each panel comprises two facing boards bonded to a core consisting of rigid plastic foam insulation, Figure 17.2. The core generally consists of expanded polystyrene (EPS). (Extruded polystyrene and polyisocyanurate cores may also be used, but they are more expensive.) The material used for the facings may be oriented strandboard (OSB) or plywood. OSB is commonly used because of its lower cost and its availability in much larger sizes. The most common thickness of OSB facing is $\frac{1}{2}$ in.

Panels are manufactured by applying structural-grade adhesive on both faces of the core and then laminating the OSB to it. The assembly is kept under pressure for the required duration. Because insulation is included in the panels, SIPs are used only in the building

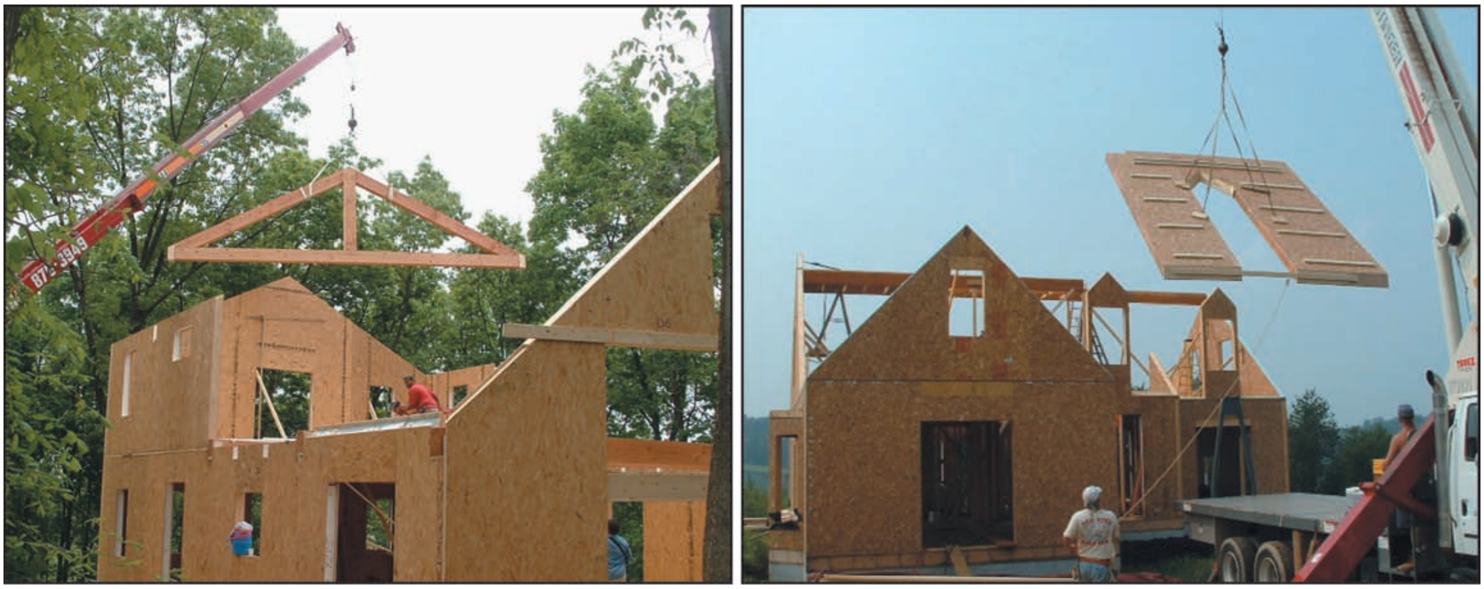


FIGURE 17.1 Two examples of typical structural insulated panel buildings under construction. (Photos courtesy of the Structural Insulated Panel Association [SIPA]).

envelope. Therefore, in a SIP building, the interior walls are generally framed with 2-by lumber and the intermediate floors are also framed with 2-by lumber or engineered wood members. The use of SIPs for an intermediate floor is, in fact, discouraged because of its lower structure-borne sound insulation. The foam in SIPs functions as an efficient acoustical bridge. SIPs may, however, be used in a floor that is required to be insulated if its lower sound-insulation value is of no concern, such as a floor over a crawl space or basement.

Although there are many similarities between the characteristics of the SIP systems of various manufacturers, SIP is a proprietary system that differs somewhat from manufacturer to manufacturer. The discussion and illustrations provided here are generic. Most SIP manufacturers have details that have been carefully developed and approved by the code authorities and should be strictly followed.

In considering the use of a SIP system, the general procedure is to send the architectural drawings of the project to the selected SIP manufacturer. Based on the analysis of the drawings, the manufacturer determines the size, shape, configuration, and thickness of the panels and prepares the necessary shop drawings for their fabrication.

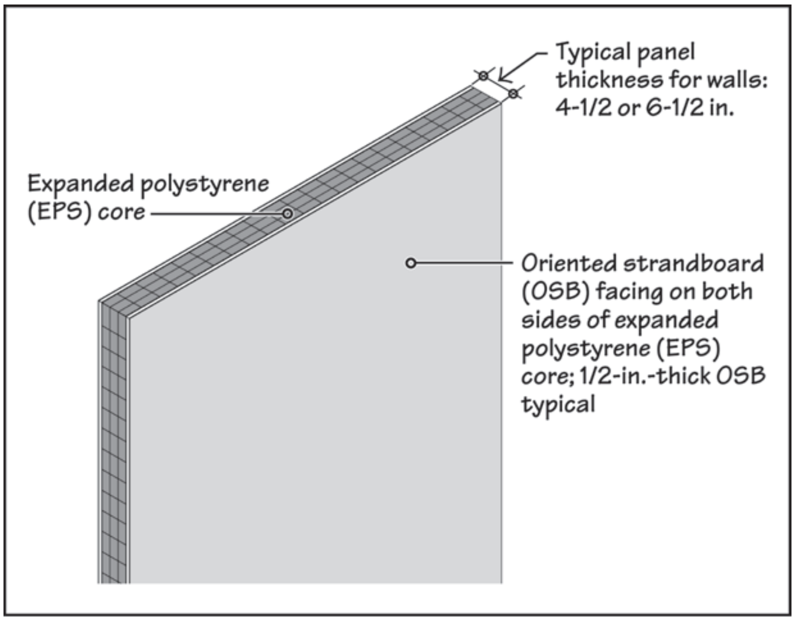

Typical panel thickness for walls: 4-1/2 or 6-1/2 in.
Expanded polystyrene (EPS) core
Oriented strandboard (OSB) facing on both sides of expanded polystyrene (EPS) core; 1/2-in.-thick OSB typical

FIGURE 17.2 Composition of a typical structural insulated panel.

After the approval of the shop drawings by the architect and the constructor, the manufacturer fabricates the panels. Each panel is uniquely identified as to its location in the building. All panels required for the project are packaged and sent to the construction site for assembly.

Because almost no cutting is required on site, the panels are shipped to the site when needed, eliminating the need for elaborate site storage facilities. The plant typically packages the panels in reverse order of their use, increasing the builder's productivity. The entire fabrication work, that is, the analysis of architectural drawings, preparation of shop drawings, and fabrication of panels, is generally computerized.

STRUCTURAL BEHAVIOR OF A SIP PANEL

Structurally, a SIP panel functions as a composite panel in which the core integrates the two facings. Thus, under an axial compressive load, even if the load is initially delivered to one facing, both facings combine to resist the load because the core transfers the load to the other, initially unloaded facing through shear mechanism.

Similar behavior comes into play when the panel is subjected to bending. Under bending, one facing is subjected to compressive stresses and the other facing is under tensile stresses. The core resists the shear stresses generated by bending. The behavior of a SIP panel is, therefore, identical to that of an I-section, where the facings function as the flanges of the I-section and the foam core functions as the section's web, Figure 17.3.

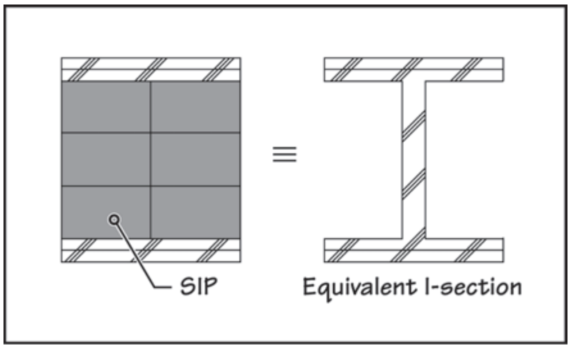


FIGURE 17.3 In carrying both axial and lateral loads, a SIP behaves as an I-section where the core functions as the web of the section and the facings as its flanges.

The core also helps to prevent the buckling of thin facings under compressive stresses, created either by the bending of the panels (in a floor or roof) or under compressive loads (in a wall). In other words, all three elements of a SIP are stressed under axial or lateral loads.

The facing-core composite behavior also comes into action in providing racking resistance to the structure where the facings and the core act together as shear walls. In a conventional wood frame building, only the exterior sheathing and the studs provide racking resistance.

PANEL SIZES

Panels are produced in various thicknesses, depending on whether they are used in walls, floors, or roofs. Wall panels are generally $4\frac{1}{2}$ in. or $6\frac{1}{2}$ in. thick. A $4\frac{1}{2}$-in.-thick SIP consists of a $3\frac{1}{2}$-in.-thick core, matching a wood light-frame wall made of 2 × 4 studs. A $6\frac{1}{2}$-in.-thick panel (with a $5\frac{1}{2}$-in.-thick core) corresponds to a wood frame wall comprising 2 × 6 studs. Panel thicknesses of $8\frac{1}{4}$ in., $10\frac{1}{4}$ in., and $12\frac{1}{4}$ in. are used for floors or roofs.

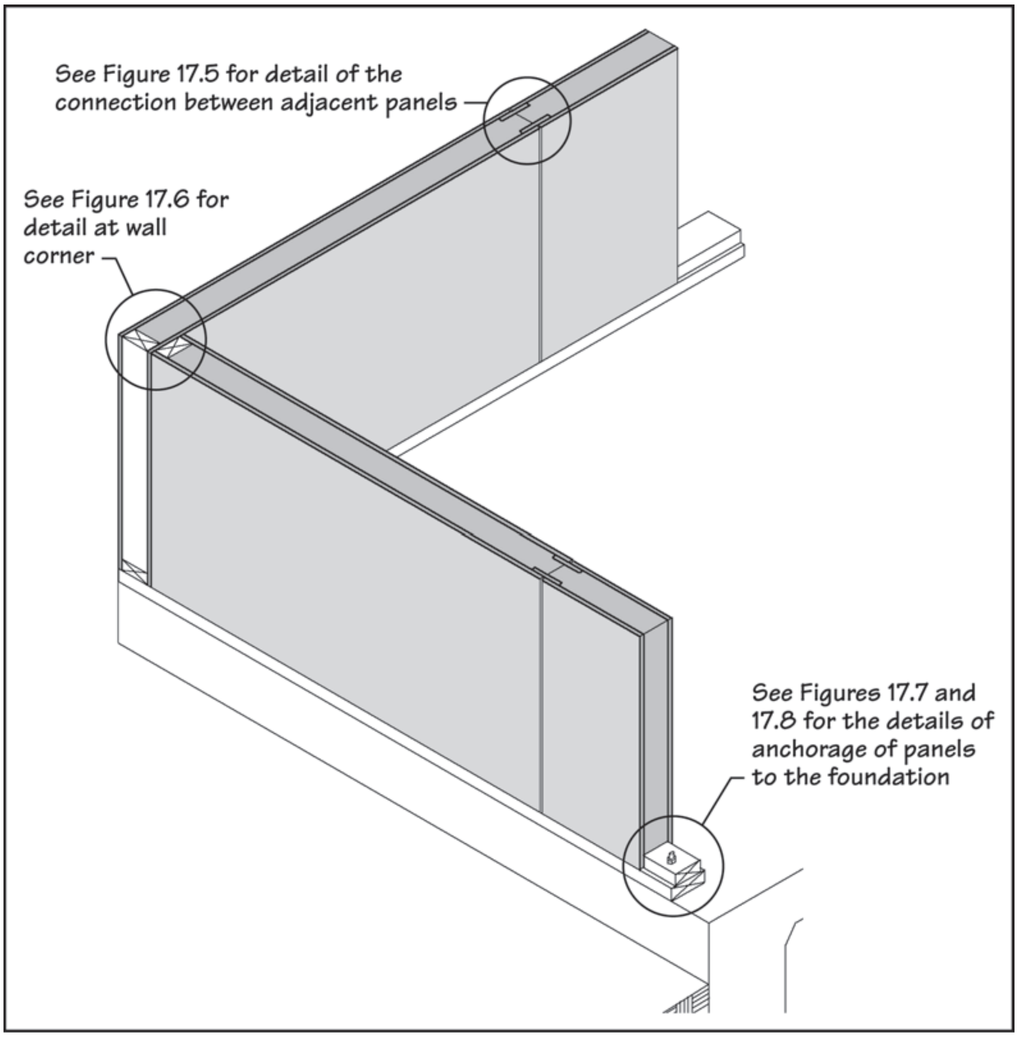
The surface dimensions (length and width) of panels vary, depending on whether lifting and placing the panels in position at the site is done manually or using hoisting equipment. Panels of up to 8 ft × 24 ft can be produced by fabricators.

17.2 SIP WALL ASSEMBLIES

In general, SIP wall panels are either 4 ft or 8 ft wide. They may be continuous over the entire height of the building or they may be only one floor tall, requiring floor-by-floor installation. The floor-by-floor installation of panels is similar to the construction of walls in a conventional WLF building, where the upper floor walls are installed over the subfloor at that level.

The details of the connection of wall panels to the foundation, between adjacent panels, at wall corners, and to the floors and roofs are critical. Figure 17.4 provides an overall view

FIGURE 17.4 General layout of exterior walls in a SIP structure.


See Figure 17.5 for detail of the connection between adjacent panels
See Figure 17.6 for detail at wall corner
See Figures 17.7 and 17.8 for the details of anchorage of panels to the foundation

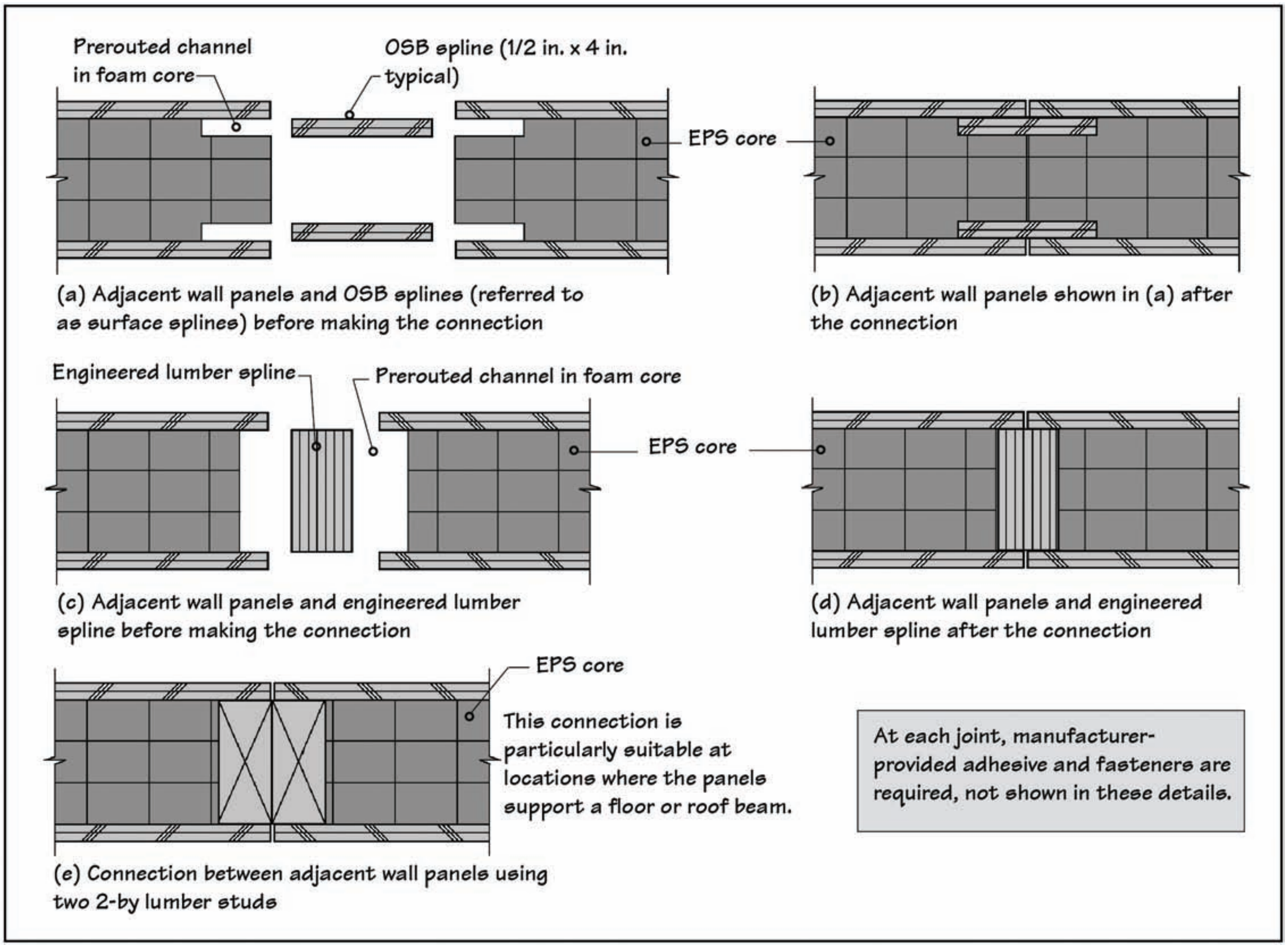

Prerouted channel in foam core
OSB spline (1/2 in. x 4 in. typical)
EPS core
(a) Adjacent wall panels and OSB splines (referred to as surface splines) before making the connection
(b) Adjacent wall panels shown in (a) after the connection
Engineered lumber spline
Prerouted channel in foam core
EPS core
(c) Adjacent wall panels and engineered lumber spline before making the connection
(d) Adjacent wall panels and engineered lumber spline after the connection
EPS core
This connection is particularly suitable at locations where the panels support a floor or roof beam.
At each joint, manufacturer-provided adhesive and fasteners are required, not shown in these details.
(e) Connection between adjacent wall panels using two 2-by lumber studs

FIGURE 17.5 Three commonly used alternative ways of connecting adjacent wall panels. These details are keyed to Figure 17.4.

of a typical panel layout. The adjacent wall panels are connected together with splines, Figure 17.5.

The splines may consist of $\frac{1}{2}$-in.-thick OSB strips (referred to as *surface splines*), engineered wood studs, or double 2-by studs, depending on the requirement of the connection. Nails, screws, and adhesives are used in a connection per the manufacturer's details.

The use of connecting splines requires the foam core to be routed and grooved to accept the splines. This operation is performed at the panel-fabrication plant so that the panels arrive at the site already routed. Chases for electrical wiring (generally $1\frac{1}{2}$ in. in diameter) are also routed before the panels are shipped to the site. Chases for other utility pipes are not included in SIPs because these pipes typically occur in the interior walls.

Figure 17.6 shows the connection between panels at a wall corner. Figures 17.7 and 17.8 show the details of the anchorage of wall panels to foundations. A two-sill-plate assembly at the foundation is commonly recommended by the manufacturers. The lower sill plate consists of preservative-treated lumber. The upper sill plate functions as a connecting spline. The details of Figures 17.7 and 17.8 ensure that the OSB facings bear directly over the lower sill plate so that the gravity load on the wall is transferred through the facings to the foundations in bearing.

There are various ways in which windows and doors can be detailed in a SIP wall. A commonly used method is shown in Figure 17.9. As stated previously, the interior partitions in a SIP building are framed by using conventional 2-by studs. Figure 17.10 shows the detail of the junction between an exterior SIP panel and an interior wall.

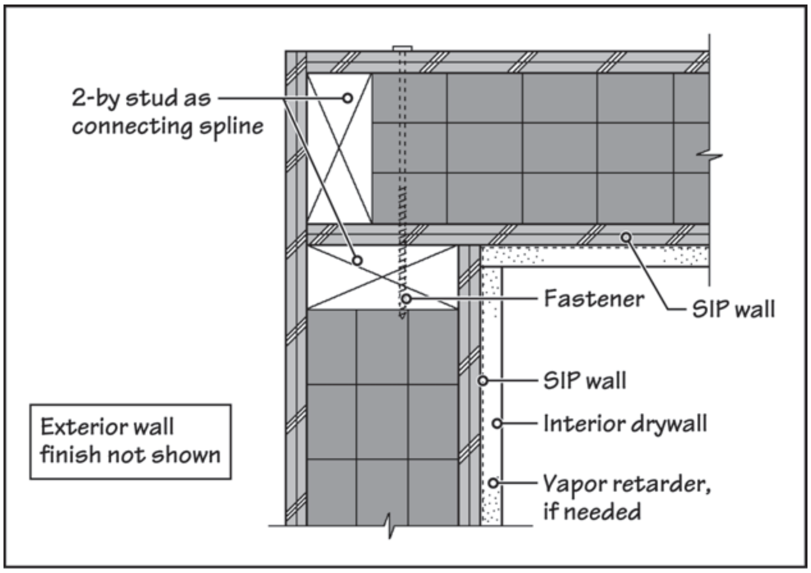

2-by stud as connecting spline
Fastener
SIP wall
SIP wall
Interior drywall
Exterior wall finish not shown
Vapor retarder, if needed

FIGURE 17.6 Typical connection at the corner of two structural insulated wall panels. This detail is keyed to Figure 17.4.

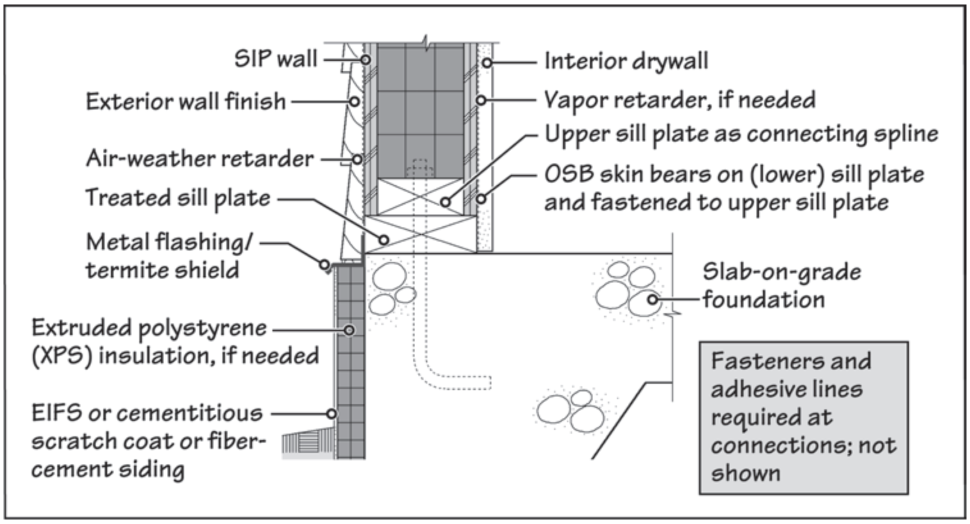

SIP wall
Exterior wall finish
Air-weather retarder
Treated sill plate
Metal flashing/ termite shield
Extruded polystyrene (XPS) insulation, if needed
EIFS or cementitious scratch coat or fiber-cement siding
Interior drywall
Vapor retarder, if needed
Upper sill plate as connecting spline
OSB skin bears on (lower) sill plate and fastened to upper sill plate
Slab-on-grade foundation
Fasteners and adhesive lines required at connections; not shown

FIGURE 17.7 Typical detail of the anchorage of structural insulated wall panels to a slab-on-grade foundation. This detail is keyed to Figure 17.4.

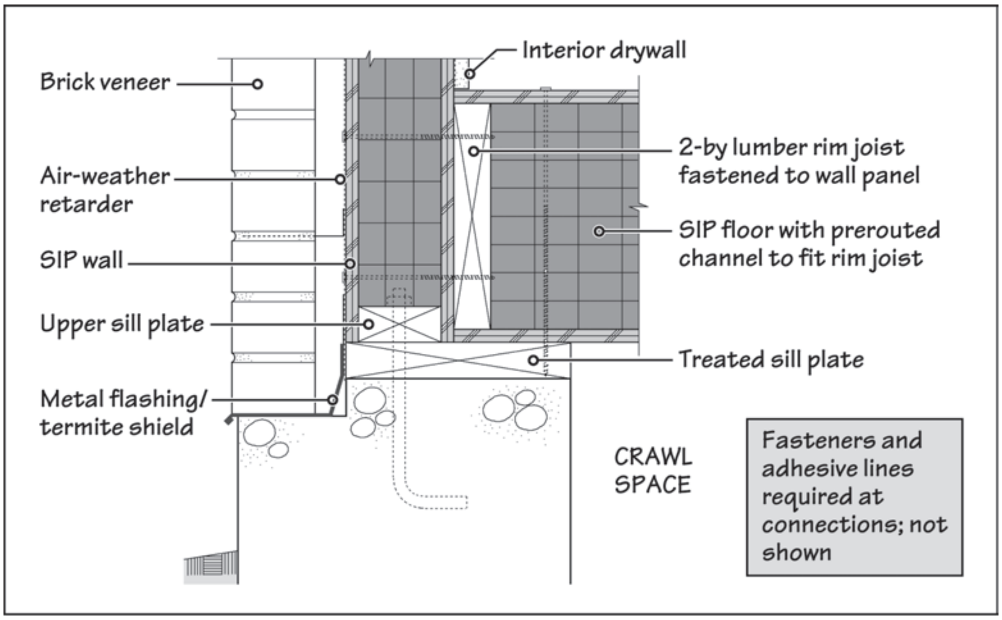

Brick veneer
Air-weather retarder
SIP wall
Upper sill plate
Metal flashing/ termite shield
Interior drywall
2-by lumber rim joist fastened to wall panel
SIP floor with prerouted channel to fit rim joist
Treated sill plate
CRAWL SPACE
Fasteners and adhesive lines required at connections; not shown

FIGURE 17.8 Typical detail of the anchorage of structural insulated wall panels to a foundation with a crawl space.

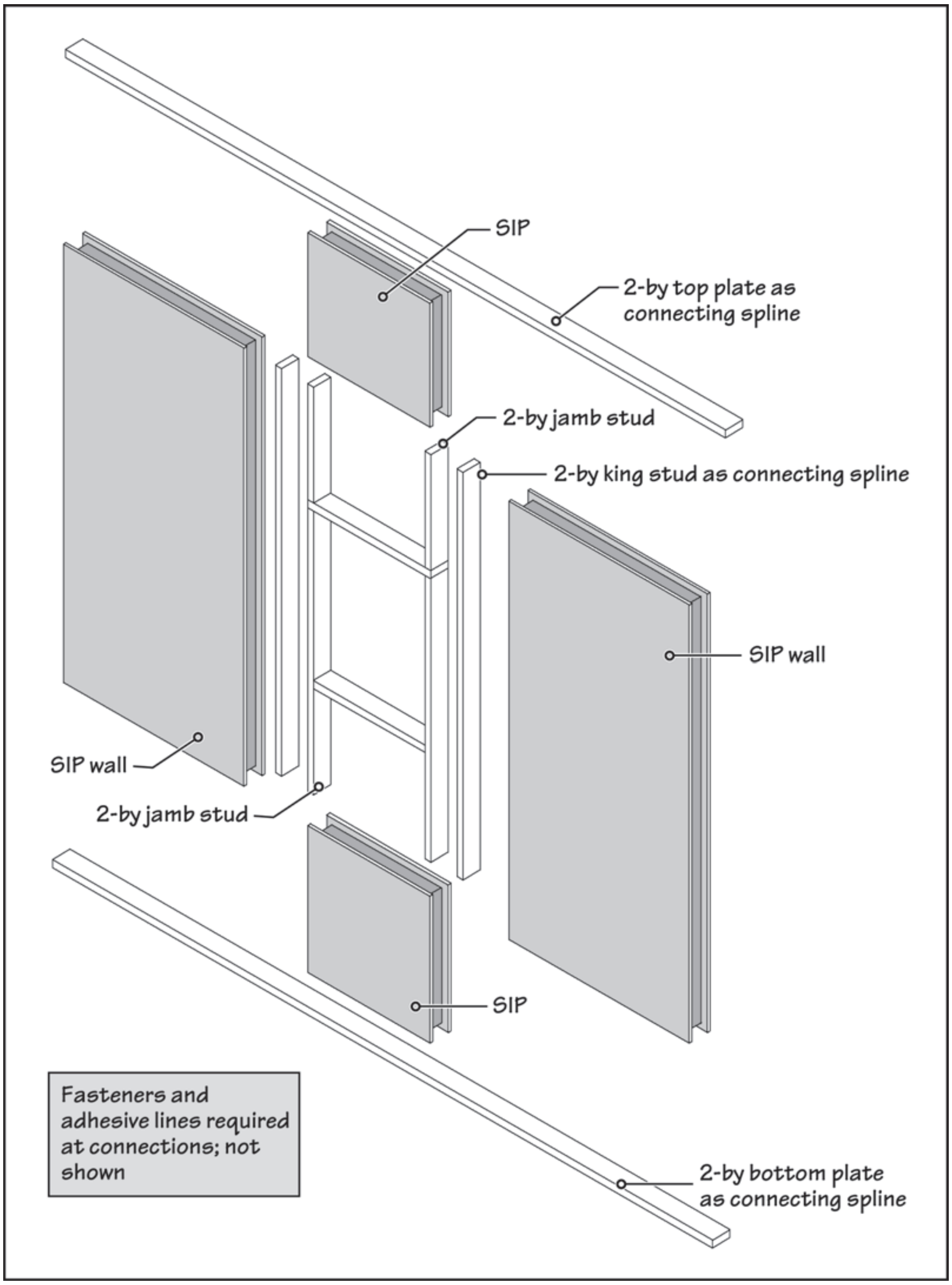

SIP
2-by top plate as connecting spline
2-by jamb stud
2-by king stud as connecting spline
SIP wall
SIP wall
2-by jamb stud
SIP
Fasteners and adhesive lines required at connections; not shown
2-by bottom plate as connecting spline

FIGURE 17.9 A typical detail of framing around a window. Framing around a door is similar.

17.3 SIP FLOOR ASSEMBLIES

As stated earlier, an intermediate floor in a SIP building is framed with 2-by lumber joists, engineered wood members (e.g., wood I-joists), or trussed joists. The floor joists may be placed on the wall panel and fastened to the top plate spline using a detail similar to that used in a conventional wood frame building, Figure 17.11.

The detail of Figure 17.11 creates a thermal bridge at the rim joist. Therefore, some SIP manufacturers recommend the detail shown in Figure 17.12, in which the floor joists are hung off the top plate spline using joist hangers. The joist hangers are top-supported, that is, fastened to the top plate in the SIPs. Where the SIPs are continuous, that is, two floors high, the floor joists are supported on joist hangers that are fastened to a ledger beam, Figure 17.13.

17.4 SIP ROOF ASSEMBLIES

Two alternative roof assemblies can be used in a SIP building. One alternative is to use any one of the various assemblies that are used in a conventional wood frame building—that is, a stick-frame rafter-ceiling assembly or wood roof truss assembly. In these assemblies, insulation is placed in the attic.

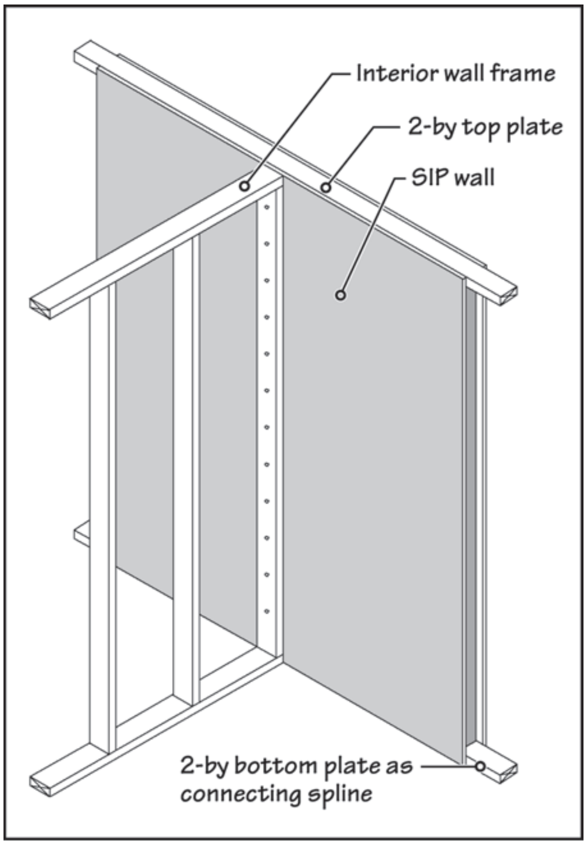

Interior wall frame
2-by top plate
SIP wall
2-by bottom plate as connecting spline

FIGURE 17.10 Connection of an interior wall to a SIP wall.

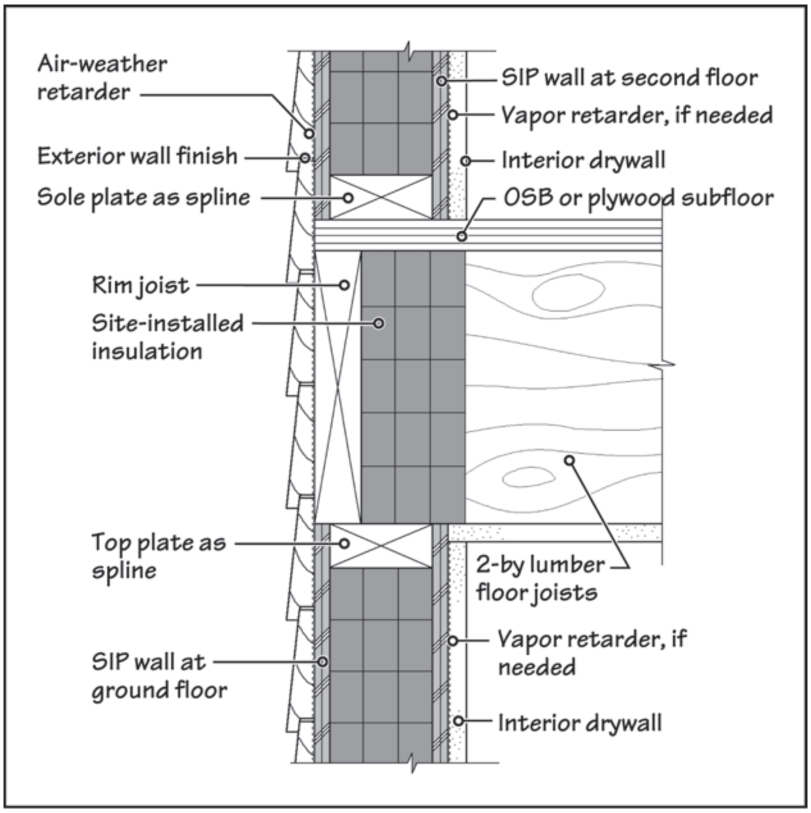

Air-weather retarder
Exterior wall finish
Sole plate as spline
Rim joist
Site-installed insulation
Top plate as spline
SIP wall at ground floor
SIP wall at second floor
Vapor retarder, if needed
Interior drywall
OSB or plywood subfloor
2-by lumber floor joists
Vapor retarder, if needed
Interior drywall

FIGURE 17.11 Detail at the junction of a SIP floor and a SIP wall. The detail is similar to that used in a conventional wood frame building. Site-installed insulation is needed behind the rim joist.

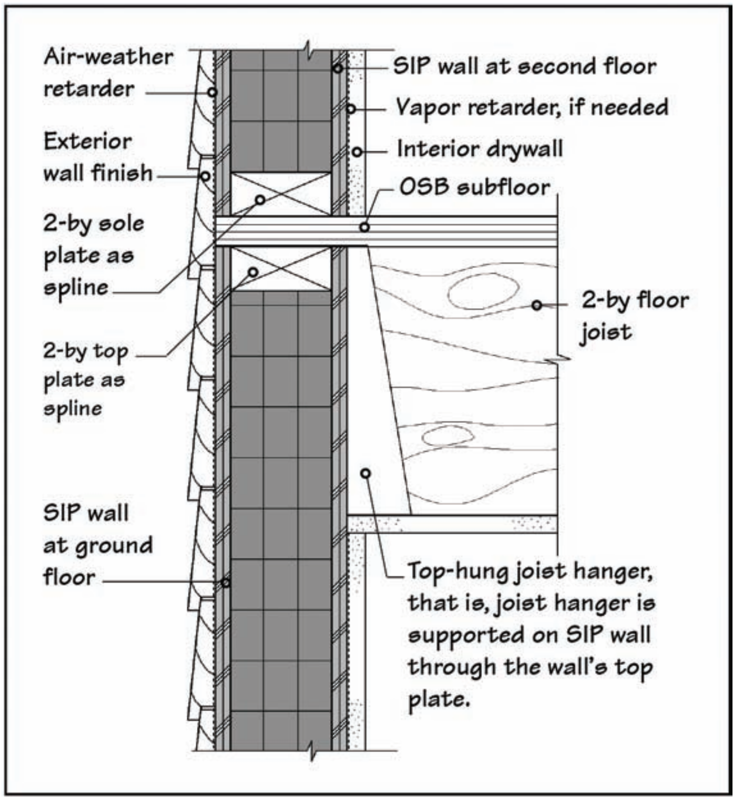

Air-weather retarder
Exterior wall finish
2-by sole plate as spline
2-by top plate as spline
SIP wall at ground floor
SIP wall at second floor
Vapor retarder, if needed
Interior drywall
OSB subfloor
2-by floor joist
Top-hung joist hanger, that is, joist hanger is supported on SIP wall through the wall's top plate.

FIGURE 17.12 Detail at the intersection of a floor and a SIP wall—an alternative to the detail in Figure 17.11. In this detail, site-installed insulation is not needed.

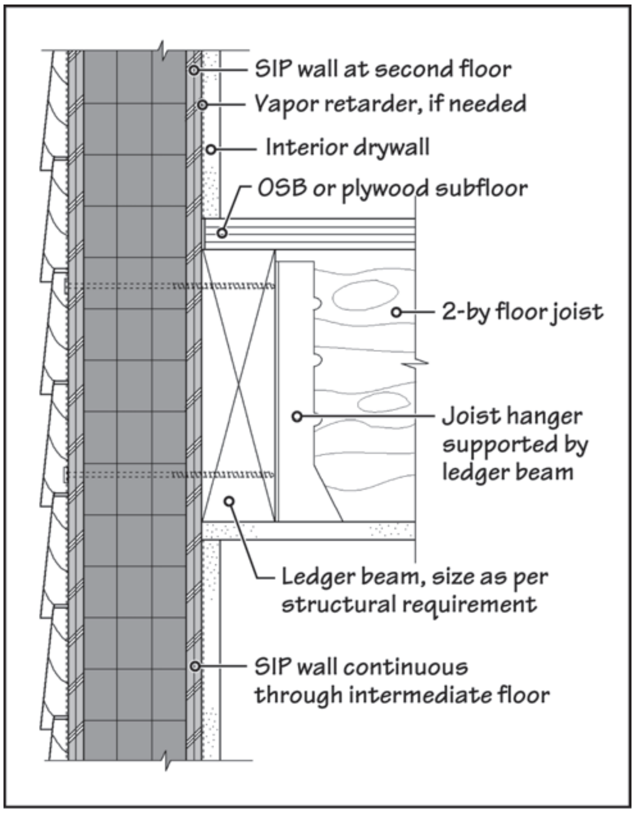

SIP wall at second floor
Vapor retarder, if needed
Interior drywall
OSB or plywood subfloor
2-by floor joist
Joist hanger supported by ledger beam
Ledger beam, size as per structural requirement
SIP wall continuous through intermediate floor

FIGURE 17.13 Detail at the intersection of a floor and a SIP wall where the SIP wall is continuous through the floor.

The second alternative is to use a SIP roof, where the roof SIPs span from the ridge beam to the exterior wall, creating a cathedral ceiling. Typical details of such an alternative are shown in Figure 17.14.

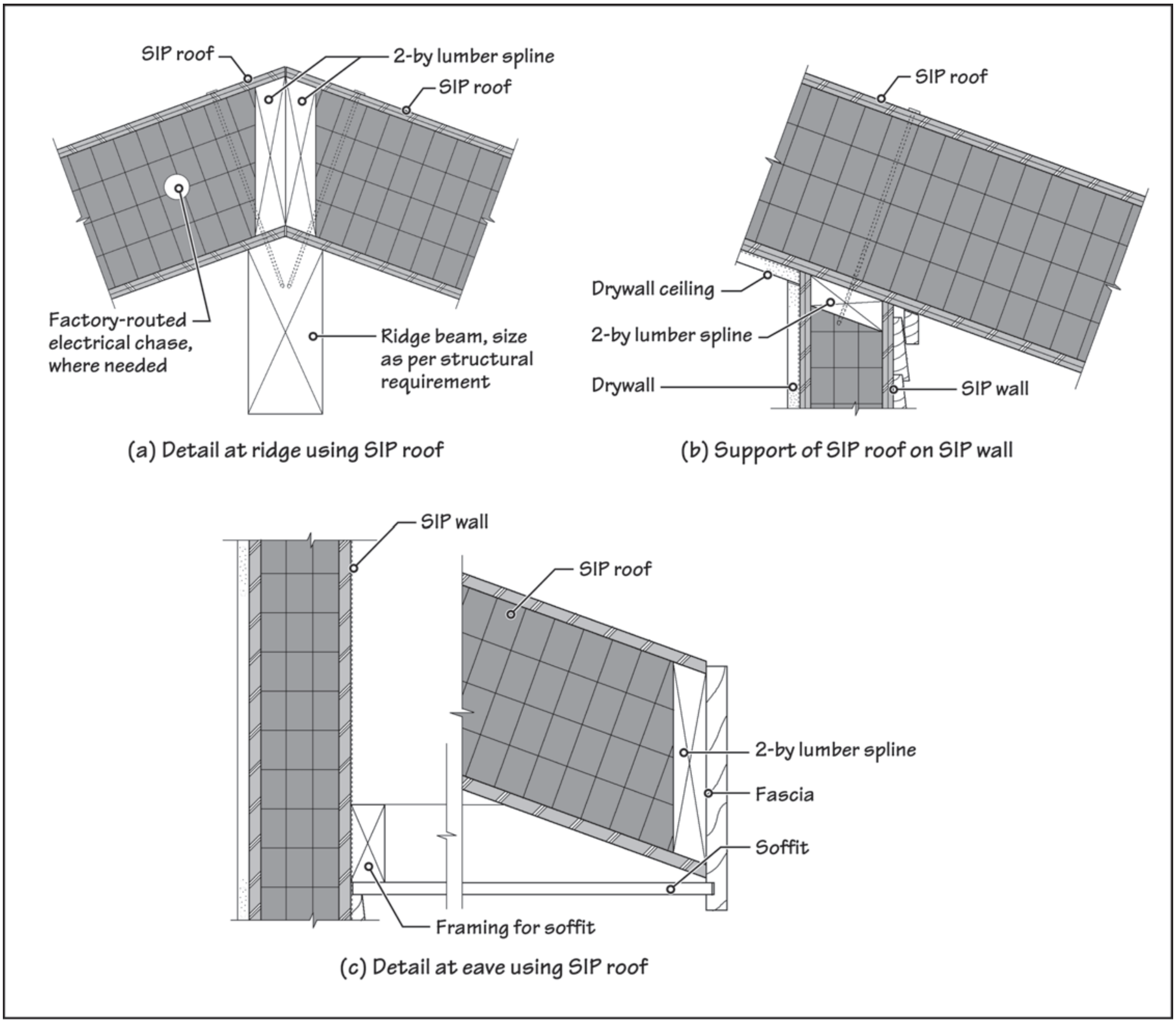

SIP roof
2-by lumber spline
SIP roof
Factory-routed electrical chase, where needed
Ridge beam, size as per structural requirement
(a) Detail at ridge using SIP roof
SIP roof
Drywall ceiling
2-by lumber spline
Drywall
SIP wall
(b) Support of SIP roof on SIP wall
SIP wall
SIP roof
2-by lumber spline
Fascia
Soffit
Framing for soffit
(c) Detail at eave using SIP roof

FIGURE 17.14 Details at the ridge and eave using roof and wall SIPs.

17.5 ADVANTAGES AND LIMITATIONS OF SIPS

The SIP system of construction has several advantages and limitations compared with the conventional WLF system.

ADVANTAGES

- *Panelization and Deletion of Insulation Subtrade:* As stated at the beginning of this chapter, panelization and deletion of the insulation subtrade in a SIP structure increase the speed and efficiency of construction.
- *Air-Weather Retarders:* Because the panels are relatively airtight, air-weather retarders are needed only for their water-resistive properties.
- *Continuous Nailable Surface:* Because OSB facings provide a continuous nailable surface, interior drywall and exterior wall finishes can be applied without having to locate the studs.
- *Pneumatic Nailers:* Although several details require the use of screws, pneumatic nailers are used extensively.
- *On-site Waste:* Very little on-site waste is produced in a SIPs structure because most members arrive at the site precut to size.
- *Energy Efficiency:* One of the major advantages of SIP is their energy efficiency. A SIP structure has virtually no thermal bridges in the envelope. The use of foam core allows no air movement within the insulation, unlike that in fiberglass insulation.

- *Fire Endurance:* SIP manufacturers claim that the fire endurance of a SIP structure matches that of a conventional wood frame structure. The absence of concealed spaces in walls and roofs deprives the fire of the oxygen required for burning.

LIMITATIONS

- *Chases:* Because the electrical chases must be prerouted in the panels, a greater amount of preplanning is necessary.
- *Squareness of Panels:* Panels must be absolutely square for a successful installation.
- *Termites and Insect Attack:* Termites and insects boring through foam insulation, which can seriously impact the structural performance of the system, must be checked with the manufacturer.
- *Long-Term Performance:* Long-term structural performance of the system depends on the long-term performance of the adhesives.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. In a SIP, the insulation generally consists of
- **a.** fiberglass.
- **b.** extruded polystyrene.
- **c.** polyisocyanurate.
- **d.** polyurethane.
- **e.** expanded polystyrene.

2. The facing in a SIP generally consists of
- **a.** OSB on both faces.
- **b.** OSB on the exterior face and gypsum board on the interior face.
- **c.** plywood on the exterior face and gypsum board on the interior face.
- **d.** plywood on the exterior face and OSB on the interior face.
- **e.** none of the above.

3. In a SIP structure, the interior walls are constructed of 4 ft × 8 ft SIP panels.
- **a.** True
- **b.** False

4. In a SIP building, exterior wall panels are typically
- **a.** 6 in. or 7 in. thick.
- **b.** $5\frac{1}{2}$ in. or 6 in. thick.
- **c.** 5 in. or 6 in. thick.
- **d.** 4 in. or 6 in. thick.
- **e.** $4\frac{1}{2}$ in. or $6\frac{1}{2}$ in. thick.

5. Adjacent structural insulated wall panels in a SIP building are connected through
- **a.** 2-by lumber studs.
- **b.** engineered lumber splines.
- **c.** OSB splines.
- **d.** any one of the above.
- **e.** special sheet metal connectors.

6. A corner between structural insulated wall panels in a SIP building requires
- **a.** a minimum of four 2-by lumber studs.
- **b.** a minimum of three 2-by lumber studs.
- **c.** a minimum of two 2-by lumber studs.
- **d.** a minimum of one 2-by lumber stud.
- **e.** no 2-by lumber studs.

7. The connection of a wall panel to a concrete foundation, as shown in this text, requires the use of
- **a.** one treated sill plate.
- **b.** two treated sill plates.
- **c.** two sill plates, one of which is treated.
- **d.** no sill plate in a SIP structure.

8. In a SIP structure, an intermediate floor may be framed with any one of the following except
- **a.** 2-by lumber members.
- **b.** wood I-joists.
- **c.** wood trussed joists.
- **d.** SIP panels.
- **e.** all of the above (without exception).

9. In a SIP structure, the roof may be framed with any one of the following except
- **a.** a rafter-and-ceiling-joist assembly consisting of 2-by lumber members.
- **b.** a rafter-and-ceiling-joist assembly consisting of wood I-joists.
- **c.** wood roof trusses.
- **d.** SIP panels.
- **e.** all of the above (without exception).

10. A SIP manufacturer generally supplies standard-size panels, which must be cut to size at the site as required by project drawings.
- **a.** True
- **b.** False

11. Similar to the conventional WLF structure, the interior gypsum board wall finish must be nailed to the studs in a SIP structure.
- **a.** True
- **b.** False

12. The maximum size of available SIP panels is
- **a.** 4 ft × 8 ft.
- **b.** 4 ft × 10 ft.
- **c.** 8 ft × 8 ft.
- **d.** 8 ft × 16 ft.
- **e.** 8 ft × 24 ft.

REVIEW QUESTIONS

1. Using a sketch and notes, explain the anatomy of a SIP. In what thickness are the panels commonly used?
2. Using sketches and notes, show two alternative ways in which two adjacent SIP wall panels are joined.
3. Using a sketch and notes, explain the support of SIP walls on a slab-on-grade foundation.
4. Explain why SIPs are not recommended for an intermediate floor but can be used for roofs.
5. List the two most important advantages and the two most important disadvantages of SIP construction in comparison with WLF construction.

CHAPTER 18

Material Steel and Steel Components

CHAPTER OUTLINE

18.1 Making of Modern Steel

18.2 Steel Skeleton and Birth of Frame Structures

18.3 Classification of Steel Components

18.4 Structural Steel—Hot-Rolled Sections

18.5 Steel Joists and Joist Girders—From Hot-Rolled Sections

18.6 Steel Roof and Floor Decks—Cold-Formed Steel

18.7 Corrosion Protection of Steel

18.8 Fire Protection of Steel

Because of its extensive use in industry, construction, and weaponry, iron is by far the most important of all metals. That is why metals are generally divided into two categories:

- Ferrous metals—metals that contain iron (the Latin term for iron is *ferrum*)
- Nonferrous metals—metals that do not contain iron (e.g., aluminum and copper)

Steel is the most important ferrous metal. Its high strength in relation to its weight makes it the material of choice for skyscrapers and long-span structures, such as sports stadiums and bridges. Its malleability and weldability allow it to be shaped, bent, and made into different types of components.

The history of development of steel has been long and arduous because the fuel technology necessary to produce temperatures high enough to melt iron ore on a large scale was not available until the early eighteenth century. The melting point of iron is 2,800°F (1,540°C). By contrast, copper's melting point is approximately 2,000°F (1,100°C)—a temperature that could be obtained in a wood or charcoal fire. That is why the use of copper and, later, bronze (an alloy of copper and tin) preceded that of steel by several centuries.

Wrought Iron—The Earliest Form of Iron

The earliest predecessor of steel was wrought iron. It was produced by heating iron ore in a charcoal fire. Though insufficient to melt the ore, a charcoal fire was sufficient to extract the oxygen from the ore, which consists of iron oxide mixed with some sand (silicon dioxide). In this reaction, carbon dioxide and carbon monoxide are driven off, and iron oxide is reduced to iron. The heat softens the ore enough to squeeze sand out by beating the ore with a hammer—a process called *working*, which led to the use of the term *wrought iron*.[*]

NOTE

A Note on Metals

Metals have a characteristic "metallic" appearance. They are good conductors of heat and electricity. Unless formed into extremely thin films, they are opaque.

With the exception of gold, pure metals are not found on the earth's surface because they react readily with other elements and form compounds. For example, iron forms iron oxide when exposed to air over a period of time. Aluminum also much more readily forms aluminum oxide. Although iron oxide separates from iron in the form of rust, aluminum oxide clings to aluminum tenaciously, forming a protective skin that resists the further oxidation of aluminum.

Pure metals are soft and malleable and are, therefore, not as useful as metals that are impure (i.e., alloyed with other metals). That is why 100% pure gold (24-carat gold) is too soft to be used for jewelry. Most gold jewelry is made from 18- to 22-carat gold. Eighteen-carat gold is 75% gold and 25% other metals (18 ÷ 24 = 75%). The softness of wrought iron—also due to its excessive purity—makes it less useful than steel.

Why Some Metals Are Precious

Platinum, gold, and silver are considered precious metals primarily because of their scarcity on the earth. If aluminum was rare and gold was as plentiful as aluminum, we would be using gold foil to wrap food and as a radiant barrier in buildings. In fact, when aluminum was first discovered, it was more precious than gold. It had the shine of gold, silver, and platinum and resisted corrosion, so it was, therefore, a perfect jewelry material.

As legend has it, Napoleon Bonaparte, emperor of France, was so impressed by this shiny new metal that at one of his banquets, the dinner plates for the royal guests were made from aluminum. The commoners at the banquet were served on silver plates. Bars of aluminum were exhibited alongside the French crown jewels at the Exposition Universelle in Paris in 1855.

Once the process of extracting aluminum was perfected, the price of aluminum dropped precipitously due to its abundance on the earth's surface, and aluminum was no longer considered a precious metal.

Although most of the sand is removed, a small amount (1 to 2%) remains in the form of silica fibers, formed by pounding during the working process. Pounding also converted the iron into fibers. Wrought iron is, therefore, fibrous in character, unlike steel, which is relatively homogeneous. The presence of sand also gives wrought iron the ability to resist corrosion. That is why wrought iron structures—the most notable being the Eiffel Tower in Paris (completed in 1889)—have survived without any corrosion protection.

Because of the use of charcoal, a tiny amount of carbon (nearly 0.02%) remained in iron. Thus, if we ignore the presence of the small percentage of silica, wrought iron is virtually pure iron. Its purity makes it a soft, malleable, and ductile material.

FROM WROUGHT IRON TO CAST IRON—DISCOVERY OF THE BLAST FURNACE

The making of wrought iron was slow and time consuming due to the repetitive working required on the ore. British industrialist Abraham Darby's development of the blast furnace in 1709 revolutionized iron making by providing a means of melting the ore on a large scale.

Darby used coke as the fuel to melt the ore instead of coal.[†] (Coal had replaced charcoal for quite some time due to the depletion of forests in England.) Coke is much stronger than coal and has a higher caloric value because it contains few or no impurities. In Darby's process, iron ore and coke were mixed together in a furnace called a *blast furnace*. Mixing the fuel with the ore provided the temperature required to melt the ore. The liquid iron was cooled to a solid state by casting it on a sand bed. The shape of these castings resembled that of a litter of newborn pigs. Therefore, the end product from the blast furnace came to be known as *pig iron*, although a more appropriate term is *cast iron*.

Darby's blast furnace replaced the semiautomated process of making wrought iron for mass production of cast iron, thereby reducing the cost of metal dramatically. Consequently, cast iron found extensive use, initially in machines, later in railroad tracks, and finally in bridges and buildings. Cast iron's high strength and moldability were exploited by architects in countless buildings, notably the Crystal Palace in England (1851) and several early skyscrapers in Chicago.

Because of the mixing of the ore with fuel, cast iron contains a high percentage (2.5 to 4%) of carbon. The presence of this much carbon makes iron brittle and unweldable but hard and resistant to corrosion and fire. Because of its hardness and corrosion resistance, cast iron is used in utility access hole covers and sanitary pipes. Wrought iron is no longer commercially produced.

Wrought iron (with nearly 0.02% carbon) and cast iron (with 2.5 to 4% carbon) represent two extremes of an iron-carbon alloy. The perfect amount of carbon in iron is 0.1% to 1.7%, producing a metal called *steel*.

The versatility of steel is its biggest plus. It is used in both structural and nonstructural components of a building—from a simple nail to a door knob to the entire structural frame of a building. It is used in almost all building types—from the extremely functional industrial warehouse to ornate and expressive museums and concert halls. It is used for 1-story to 100-story structures. In fact, for most contemporary commercial buildings, the only choice for the structural system is between steel and concrete.

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[*] According to *Webster's New Collegiate Dictionary*, the term *wrought* means "worked into shape by artistry or effort, or beaten into shape by tools".

[†] Coke is the residue left over from heating coal in the absence of oxygen. Charcoal is the residue left over by heating wood in the absence of oxygen. Coke is sometimes called *cooked coal*.

Because of steel's versatility and extensive use, three chapters in this text have been devoted to steel construction. This chapter deals with steel as a material, that is, the manufacture of steel, types of steel and steel components, and steel's durability concerns—corrosion and fire protection. The metallurgy of steel being complex, the details of its manufacture are discussed only to the extent that they help us understand its applications. The aspects of sustainability are covered in terms of both manufacturing and applications. The following two chapters (Chapter 19 and 20) deal with design and construction aspects of steel structures.

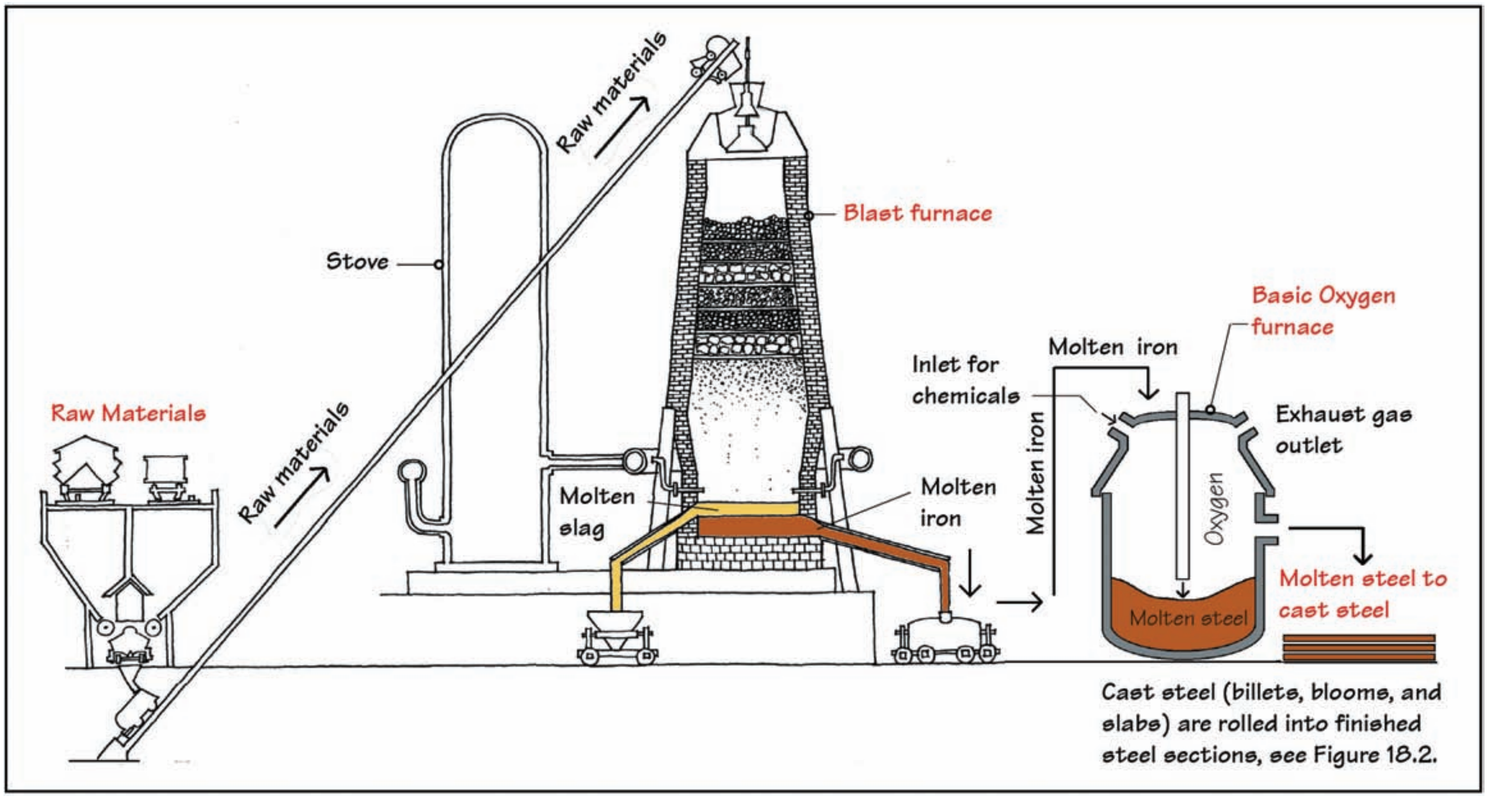
18.1 MAKING OF MODERN STEEL

Extracting carbon from cast iron to obtain the so-called perfect iron-carbon alloy was a major metallurgical problem of the nineteenth century. It was finally resolved by the development of the basic oxygen furnace (BOF) by Henry Bessemer in 1855. In the BOF, the excess carbon in molten pig iron is converted to carbon dioxide by blowing oxygen through it, leaving behind that perfect iron-carbon alloy—steel. After the discovery of the BOF, the electric arc furnace was developed, which obtains the same end result as the BOF.

MAKING STEEL FROM VIRGIN IRON ORE—THE INTEGRATED MILL METHOD

The traditional method of making steel is by using an *integrated mill*, so called because it converts the iron ore into a finished steel product (e.g., steel I-beams) by using a number of intermediate processes—all integrated into one large complex. The most important part of an integrated mill is the blast furnace, a huge steel cylinder whose interior is lined with refractory bricks, Figure 18.1.

The raw materials—iron ore, coke, and limestone—are charged into the furnace from the top in alternate layers so that the three materials are mixed together. Limestone acts as a flux. A flux is a material that removes impurities and reduces the melting point of the main raw material—iron ore. Hot air from the stove is fed into the furnace from the bottom of the stack, which ignites the coke. As the iron ore and limestone melt, they travel down the stack and settle at the bottom of the furnace. The molten material consists of two parts: molten iron and molten slag.



Cast steel (billets, blooms, and slabs) are rolled into finished steel sections, see Figure 18.2.

FIGURE 18.1 This illustration shows the process of manufacturing steel in an integrated mill. Blast furnace and basic oxygen furnace (BOF) are the two (of the three) major components of an integrated mill. Raw materials (iron ore, limestone, and coke) are fed into the blast furnace, which yields molten iron. Molten iron is used as a charge for BOF. In BOF, oxygen is blown into molten iron that converts the carbon in iron to carbon dioxide, leaving behind molten steel. Molten steel is cast into billets, blooms, and slabs for rolling into finished steel sections. A rolling mill is the third major component of an integrated mill.

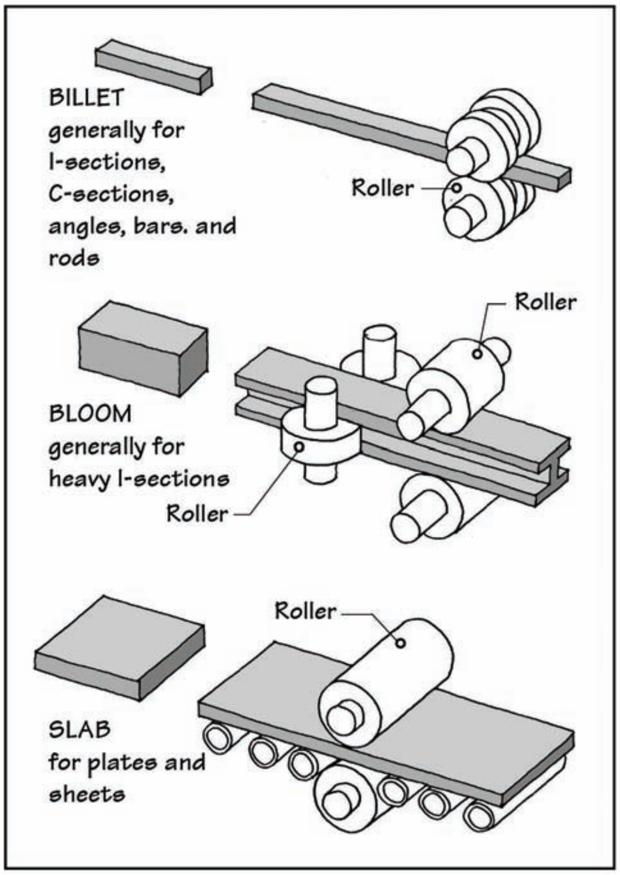

BILLET
generally for I-sections, C-sections, angles, bars. and rods
Roller
Roller
BLOOM
generally for heavy I-sections
Roller
Roller
SLAB
for plates and sheets

FIGURE 18.2 Process of hot rolling to obtain finished steel sections. In this process, billets, blooms, and slabs, obtained from the basic oxygen furnace, are reheated to virtual softening and rolled to the required cross sections as shown.

The *slag* is essentially molten limestone, but it also contains molten sand and other elements present in iron ore. Being lighter, molten slag floats over molten iron. Therefore, both slag and molten iron are drained separately from the bottom of the furnace.

Molten iron from the blast furnace is transported to BOF. Here oxygen is blown into molten iron, which converts the carbon (in iron) to carbon dioxide. At this stage, small quantities of a few other metals, such as copper, nickel, chromium, and so on, are added to the furnace to obtain the steel with the desired chemistry. The molten steel goes through continuous casting that yields long, rectangular-shaped members, called *billets*, *blooms*, or *slabs*, distinguished by their cross-sectional dimensions.

Billets, blooms, and slabs are reheated and rolled into the finished steel cross sections. Billets are of smaller cross section than blooms and are used for making I-sections, C-sections, angles, bars, and rods. Blooms are used for heavier I-sections. From slabs, steel plates and sheets are obtained, Figure 18.2.

SUSTAINABLE STEEL MANUFACTURING—THE MINI-MILL METHOD

A method increasingly used for making steel is one that recycles steel-based scrap from automobiles, transport vehicles, machinery, and so on, instead of using the virgin ore. This requires a much smaller outlay compared to the integrated mill, and the related setup is called the *mini mill*. The steel obtained from a mini mill is more economical and also more sustainable than that obtained from an integrated mill. Consequently, the number of integrated mills has declined over the years. However, they continue to be used because of the increase in steel demand and also because some specialty steel products can only be made in an integrated mill.

In the mini-mill method, steel scrap is charged from the top into a large furnace called an *electric arc furnace* (EAF). An EAF has three graphite electrodes that produce a high-temperature arc that converts the scrap into molten steel—three electrodes because of the three-phase electric power, Figure 18.3. Calcium oxide (lime) and magnesium oxide are fed into the EAF from a side door as needed. These materials form a foamy slag on melting. The foam insulates the furnace lining from the high temperature of the arc.

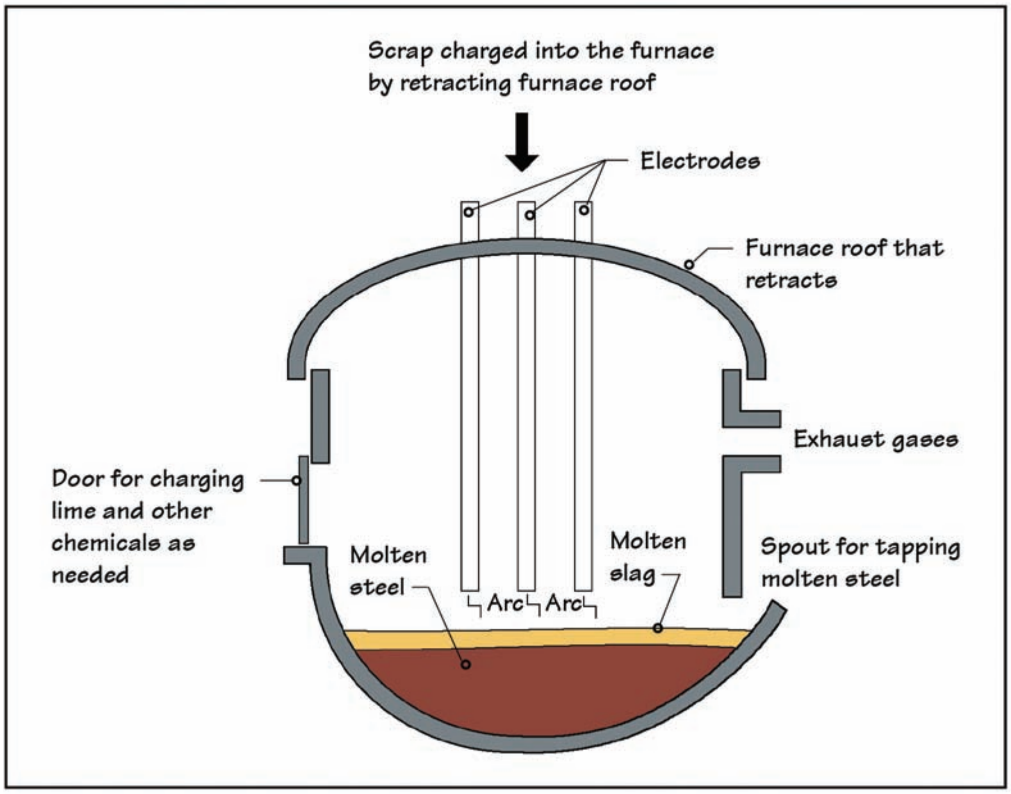

Scrap charged into the furnace by retracting furnace roof
Electrodes
Furnace roof that retracts
Exhaust gases
Door for charging lime and other chemicals as needed
Spout for tapping molten steel
Molten steel
Molten slag
Arc
Arc

FIGURE 18.3 An electric arc furnace (EAF) converts scrap steel into molten steel. This requires the use of lime and other chemicals, which are fed into the furnace as and when needed through a side door. The furnace has a retractable roof to allow the charging of steel scrap. Molten steel from the EAF is sent to a vessel (called a ladle) to modify its chemistry as needed. Molten steel from the ladle is cast into billets, blooms, and slabs, and subsequently reheated and rolled into finished cross sections.

The molten steel from the EAF is transported to a ladle (a refractory-lined vessel) where the steel chemistry is modified by adding the required chemicals. From the ladle, molten steel goes through continuous casting to billets, blooms, or slabs and is rolled into the desired cross sections in exactly the same way as in an integrated mill. Some mini mills cast billets into dog-bone cross-sectional profiles from which I-section or H-section members are made. These billets are called *near-net-shape billets* or *beam blanks*, Figure 18.4. Rectangular-shaped billets, Figure 18.5, are used for making angles, bars, and rods.

The mini-mill method relies on scrap recycling. A large scrap storage yard and a shredder are the two most important parts of a recycling plant, Figures 18.6 and 18.7. After shredding, the scrap is separated into ferrous and nonferrous scrap using magnetic separation. Nonferrous scrap is further separated into metals (copper, aluminum, etc.) and nonmetals (plastics, rubber, fabric, etc.) by floatation technology in which separation is obtained through a float-sink mechanism, that is, based on density variations between various types of nonferrous scrap. After the scrap goes through shredding and separation, it is stored in the yard as feed for the EAF, Figure 18.8. Most mini mills have a large scrap recycling facility within or close to the mill.

SLAG—A WASTE PRODUCT FROM STEEL MANUFACTURING

Slag is a waste product from the blast furnace and the electric arc furnace. It has many uses—as a lightweight aggregate, as a raw material in the manufacture of Portland cement, and in the manufacture of insulation, called *slag wool*. Slag wool is noncombustible and is similar to fiberglass in its thermal properties.

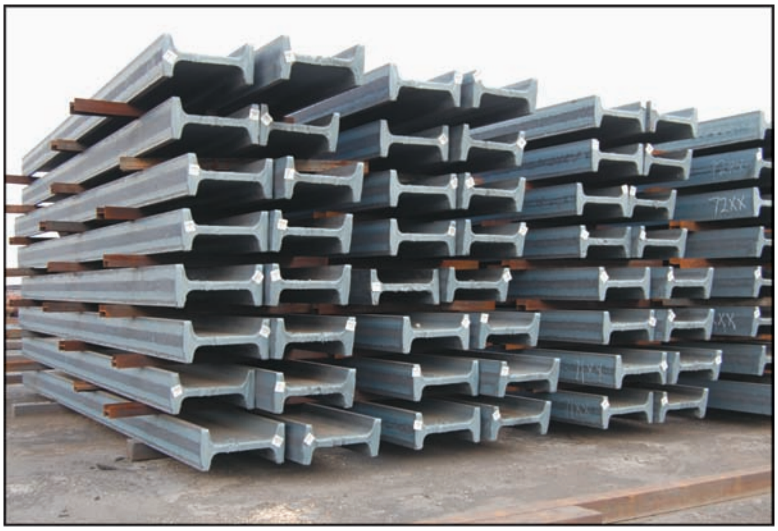


FIGURE 18.4 Some mini mills produce near-net-shape billets (also called beam blanks). These are subsequently rolled into I-sections.

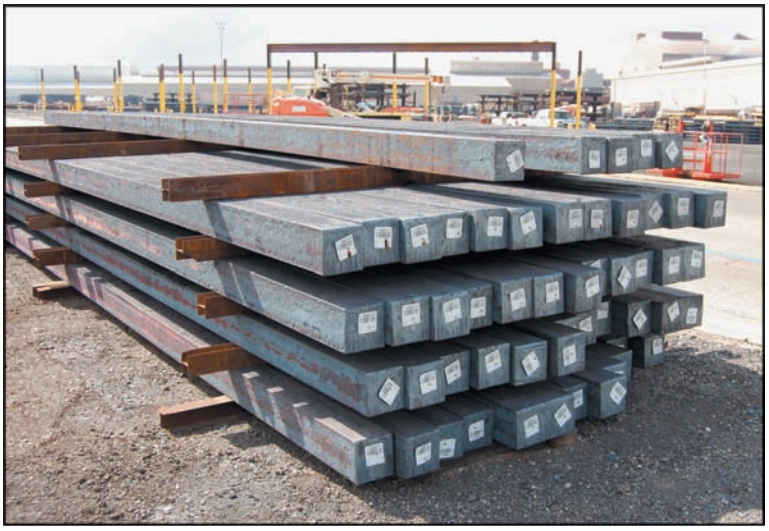


FIGURE 18.5 Rectangular-shaped billets used for rolling into channels, angles, bars, and rods.

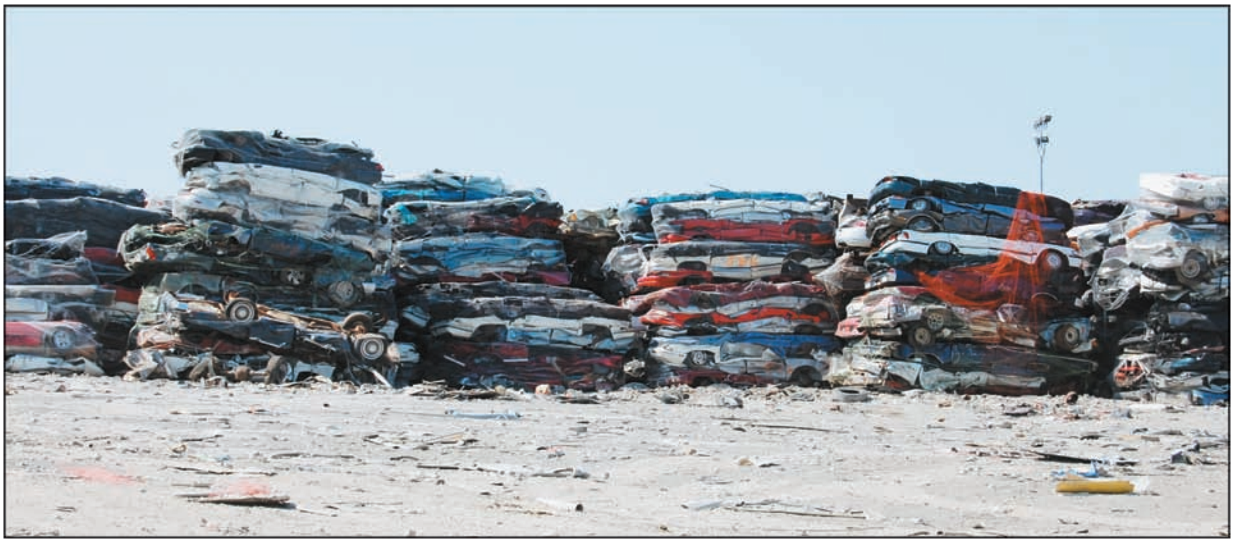


FIGURE 18.6 Crushed cars in the scrap yard of the Gerdau Ameristeel Plant in Midlothian, Texas.

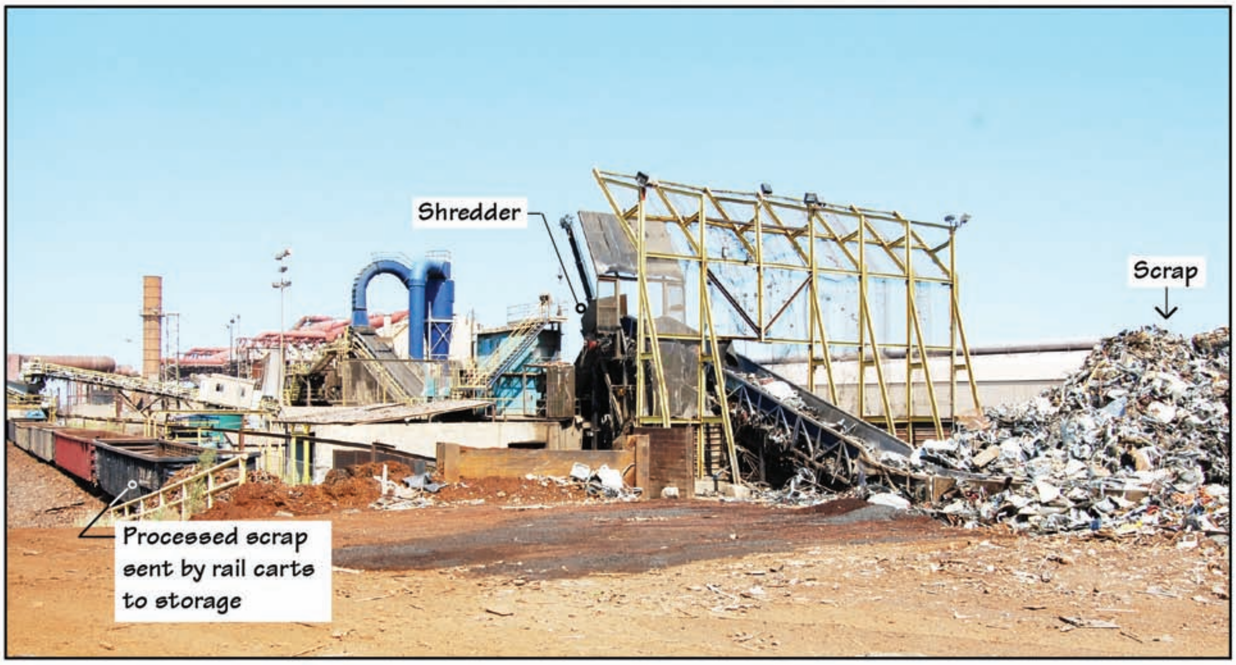

Shredder
Scrap
Processed scrap sent by rail carts to storage

FIGURE 18.7 A scrap shredder in the Gerdau Ameristeel Plant in Midlothian, Texas. After the scrap is shredded, it is separated into ferrous and nonferrous parts through magnetic separation. The ferrous scrap is then sent by rail carts to storage, ready for feed into the electric arc furnace; Figure 18.8.

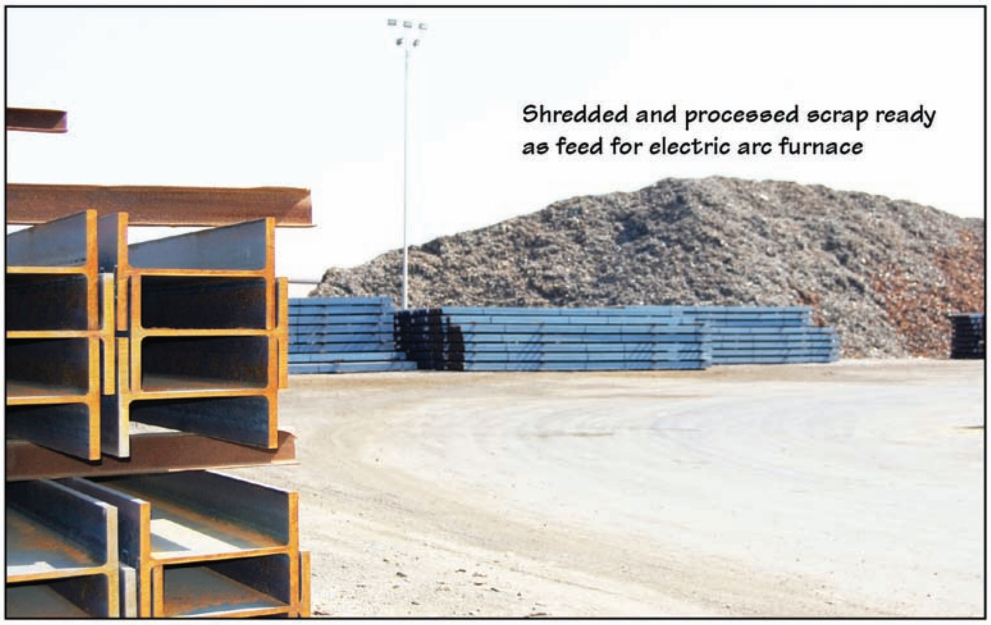

Shredded and processed scrap ready as feed for electric arc furnace

FIGURE 18.8 A view of the yard of the Gerdau Ameristeel Plant in Midlothian, Texas, showing the shredded ferrous scrap in the background and finished steel sections in the foreground.

18.2 STEEL SKELETON AND BIRTH OF FRAME STRUCTURES

From the perspective of design and construction professionals, a major significance of the discovery of steel lies in the birth of a structural system that initially came to be known as a *skeleton cage* [Ref. 18.1] because a steel building under construction, with its linear, slender elements (columns and beams), looks like a cage until the surface elements (floor and roof decks) are in place, Figure 18.9. (Some other terms used in place of *steel cage* were *steel skeleton* and *skeleton frame*.) By contrast, a reinforced concrete structure does not have the appearance of a skeleton because the surface elements (floor and roof slabs) are constructed monolithically with corresponding floor and roof beams.

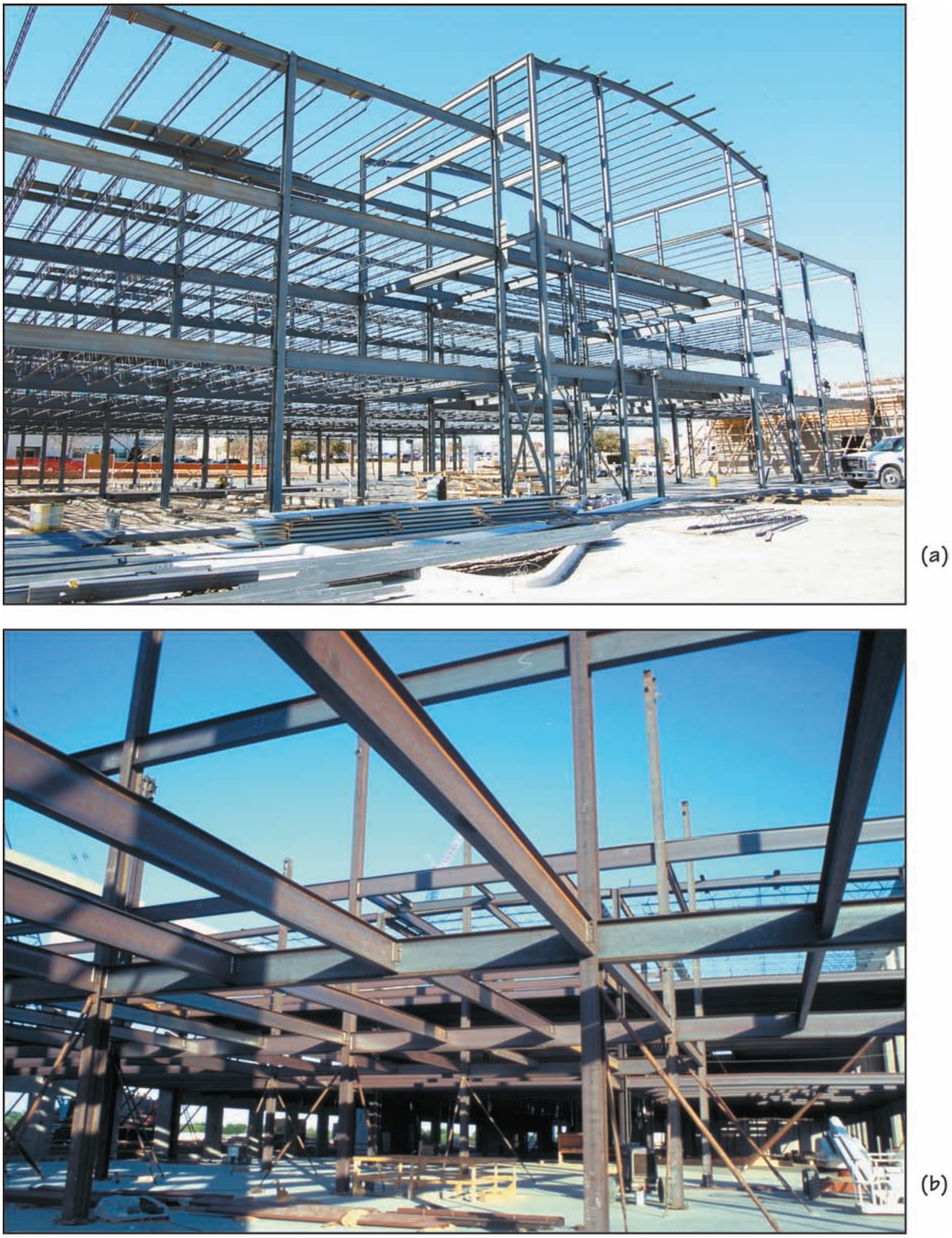


FIGURE 18.9 A steel building under construction has the appearance of a skeleton. Therefore, when steel buildings first appeared in Chicago toward the end of the nineteenth century, the terms skeleton cage, steel skeleton, and skeleton frame were coined to describe their appearance.

The terms *skeleton cage* and *skeleton frame* were in time replaced by the term *frame*, and the structural system, consisting of linear (or curvilinear) members, came to be known as a *frame structure*, a term likely to have been borrowed from *picture frame*. An additional part of the definition of a frame structure is that it is not a *load-bearing wall structure*, a structural system used for all significant buildings prior to the discovery of the frame structure. The load-bearing wall system is still used (see Chapter 26), and the structural system of most contemporary buildings is either a frame structure, a load-bearing wall structure, or a combination thereof.

In a load-bearing wall structure, the walls function as both structural and space-organizing elements. In a frame structure, on the other hand, the frame performs the structural function and the walls are used primarily for spatial organization. The separation of the two functions provided architects with a means of expression that was not available in load-bearing wall structures. (A brief introduction to the principles of frame structures is given in Principles in Practice at the end of Chapter 19.)

18.3 CLASSIFICATION OF STEEL COMPONENTS

Steel may be classified in a number of ways. For design and construction professionals, three classification systems are important: (a) classification based on steel's application, (b) classification based on steel strength, and (c) classification based on steel metallurgy.

APPLICATION-BASED CLASSIFICATION

In this classification, steel may be classified as:

- Structural steel
- Cold-formed steel
- Reinforcing steel
- Prestressing (posttensioning) steel

Structural steel members include steel cross sections, such as I-sections, H-sections, T-sections, C-sections (channels), L-sections (angles), plates, pipes, and rectangular tubes (hollow sections). They are produced by heating billets or blooms and rolling them to the required cross-sectional profile. They are also called *hot-rolled sections* and are primarily used to form the structural frame of a steel building, Figure 18.10.

Angles and T-sections are also used to fabricate trusses by welding. Light trusses are referred to as *steel joists* and *steel joist girders*. Heavier steel trusses are made from pipes, tubes, and I-sections. Details of structural steel members are discussed later in this chapter.

Cold-formed steel members are made from thin sheets of steel by bending sheets to various corrugated profiles at room temperature, hence the term *cold-formed*. Because cold-formed steel members are lightweight, cold-formed steel is also called *light-gauge steel*. Hot rolling cannot produce sheets thin and flat enough to match those produced by the cold forming process. Cold-formed steel is used in roof and floor decks (see Figure 18.10), which are further discussed in this chapter.

Another common application of cold-formed steel is in interior partition walls of buildings of the noncombustible construction type (Type I and Type II construction; see Chapter 7) because building codes do not allow the use of wood stud walls in such buildings. Cold-formed steel is also used in load-bearing applications (in walls, floors, and roofs) of a building as a substitute for wood light frame, Figure 18.11. Chapter 20 covers cold-formed steel construction.

Reinforcing steel is in the form of deformed round bars (also called *rebars*) that are used in concrete slabs, beams, and columns. Details of concrete reinforcing steel are presented in Chapter 21. *Prestressing steel* is used in precast concrete or posttensioned concrete members as a replacement for (or in conjunction with) reinforcing steel. Prestressing steel and posttensioning steel are identical products and are discussed in Chapter 22.

STRENGTH-BASED CLASSIFICATION

As stated in Section 18.1, steel is alloyed during manufacturing with a small percentage of other metals to obtain steels that vary from each other with respect to a few important properties, such as the yield strength, tensile strength, and corrosion resistance. The most commonly used steel for framing members (W-shape columns and beams) in contemporary buildings is A992, with a yield strength of 50 ksi. The yield strength of steel is also referred to as the *steel's grade*. Thus, steel with a yield strength of 50 ksi is called *grade 50 steel*.

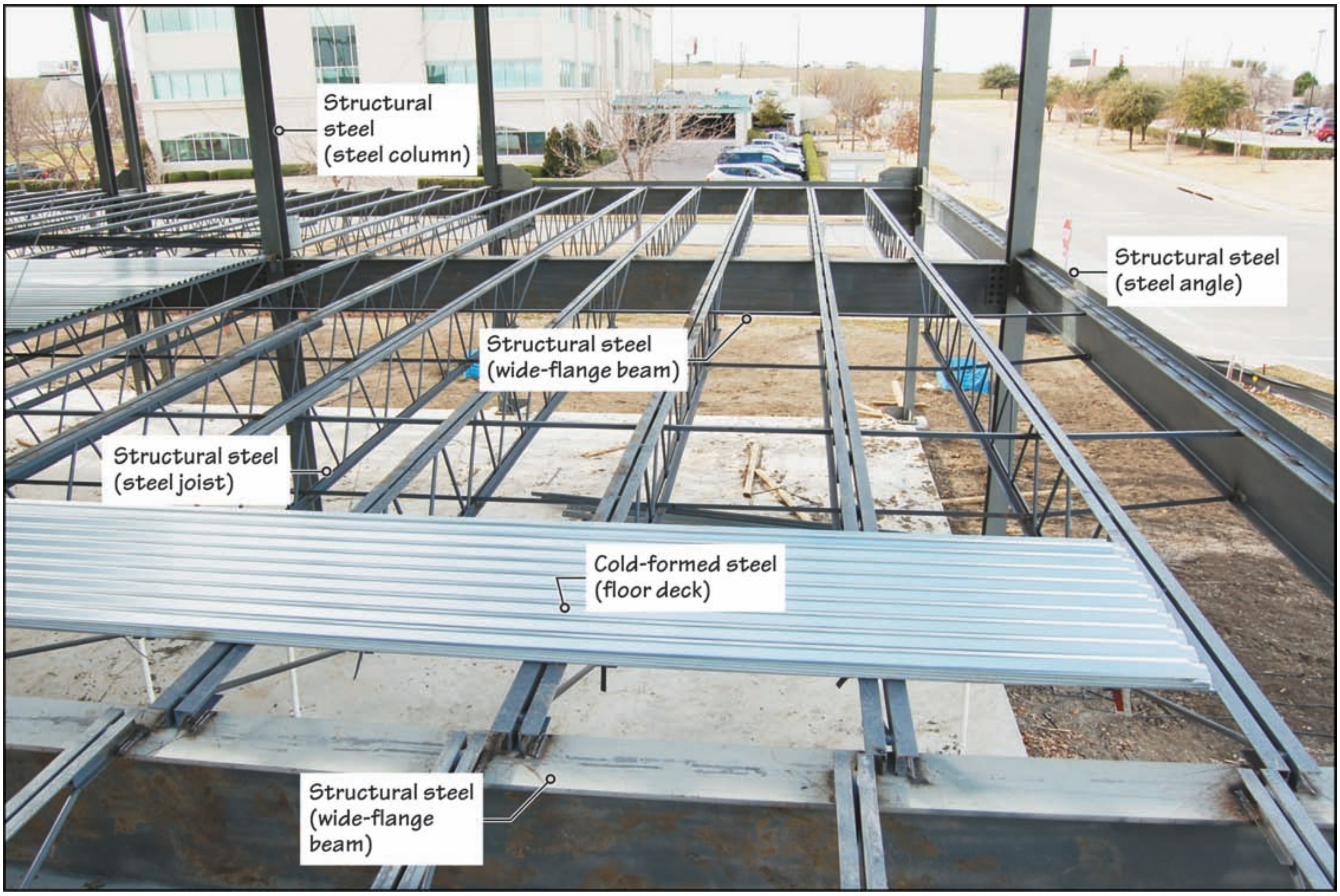

Structural steel (steel column)
Structural steel (steel angle)
Structural steel (wide-flange beam)
Structural steel (steel joist)
Cold-formed steel (floor deck)
Structural steel (wide-flange beam)

FIGURE 18.10 All components used in the structural frame of this building (columns, beams, and joists) are made of hot-rolled steel sections, referred to as structural steel. The floor deck is made of cold-formed steel.

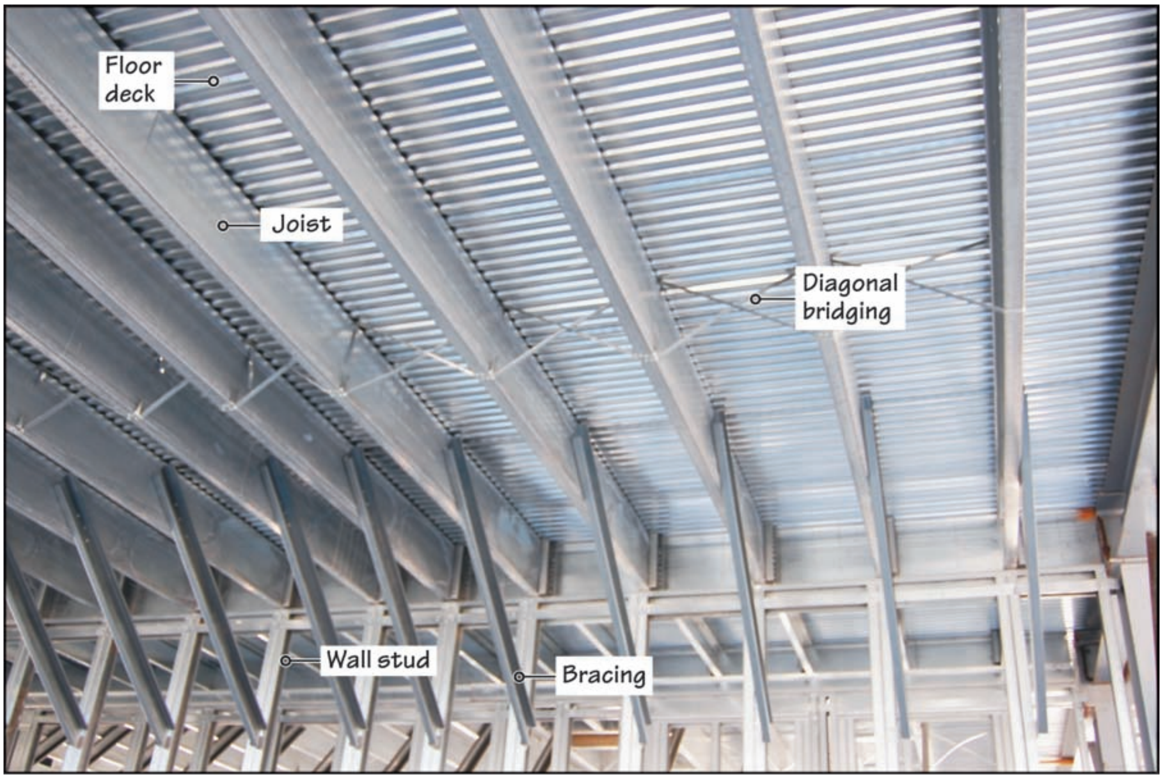

Floor deck
Joist
Diagonal bridging
Wall stud
Bracing

FIGURE 18.11 All components (floor deck, joists, wall studs, and bracing members) used in the structural framing of this building are made of cold-formed steel. The framing of this building is similar to that of a wood light-frame building (see Chapter 20).

Prior to the production of A992 steel, A36 steel (grade 36) was the building industry's standard. Today, A36 steel is used mainly for plates, angles, and channel sections.

METALLURGY-BASED CLASSIFICATION

A simple metallurgical distinction between the steels used in building construction is (a) *carbon steel* and (b) *alloy steel*. Carbon steel contains 0.1% to 0.3% carbon plus some other metals whose minimum percentage is not specified. Changing the amount of carbon between 0.1% and 0.3% changes steel's properties. Increasing the amount of carbon increases steel's strength but reduces its ductility and formability, and vice versa. Thus, because formability is important, sheet steel is made from *low-carbon steel*. Most steel used in building construction is carbon steel.

Alloy steel contains other metals to change steel's properties. *Weathering steel* and *stainless steel* are alloy steels. Chromium is the primary alloying metal in stainless steel.

18.4 STRUCTURAL STEEL—HOT-ROLLED SECTIONS

Because of the large financial outlay required in producing structural steel sections, design and construction professionals must select them from the standard shapes and sizes. Custom-rolled sections are not available. As previously stated, they are available in cross-sectional shapes of I, C, L, and T, pipes, tubes, round and rectangular bars, and plates, Figure 18.12.

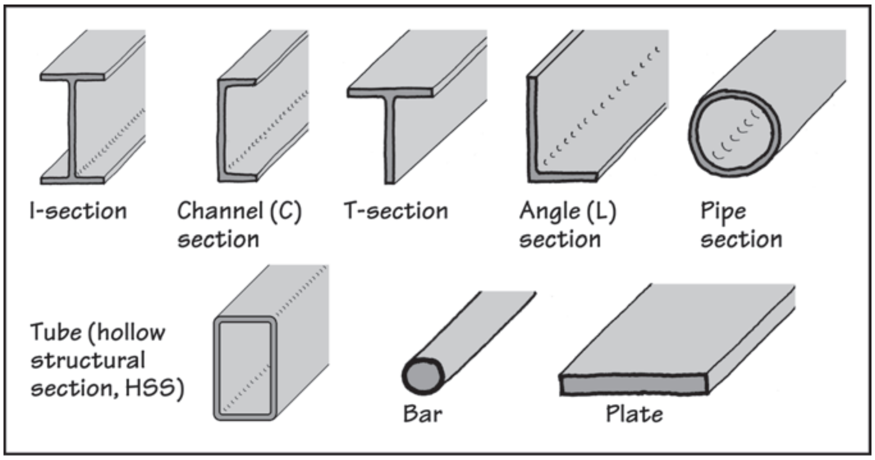


FIGURE 18.12 Commonly used structural steel sections.

I-SECTIONS

Structural steel I-sections may be classified into four shapes:

- W-shapes
- S-shapes
- HP-shapes
- M-shapes

In a W-shape, the interior surfaces of the flanges are parallel. In an S-shape, the interior surfaces of the flanges are inclined at a slope of 2:12, Figure 18.13.

Another difference between W- and S-shapes is that, for the same depth, the flanges in a W-shape are wider than those in an S-shape. That is why a W-shape is called a *wide-flange section*. Because of the parallel flange surfaces and wide flanges, W-shapes are the ones most often used for beams and columns. S-shapes (also called *American standard* shapes) are used in cranes and rails.

Each W-shape is designated by two numbers: the first number refers to the nominal depth of the section (in inches), and the second number gives its weight for a 1-ft length (pounds per foot). For example, W21 × 68 means that the nominal depth of the section is 21 in. and its nominal weight is 68 lb/ft. The nominal depth is the section's approximate (not exact) depth.

W-shapes are available in a large range of sizes and weights, from W40 × 503 to W4 × 13. A few manufacturers also make 44-in.-deep W-shapes. Several W-shapes share a common nominal depth but have different flange widths, flange thicknesses, and web thicknesses. Sections such as W14 × 132, W14 × 82, and W14 × 53 have different weights but the same nominal depth.

NOTE

Nominal Depths of W-Shapes

W44, W40, and W36

W33, W30, W27, W24, W21, and W18

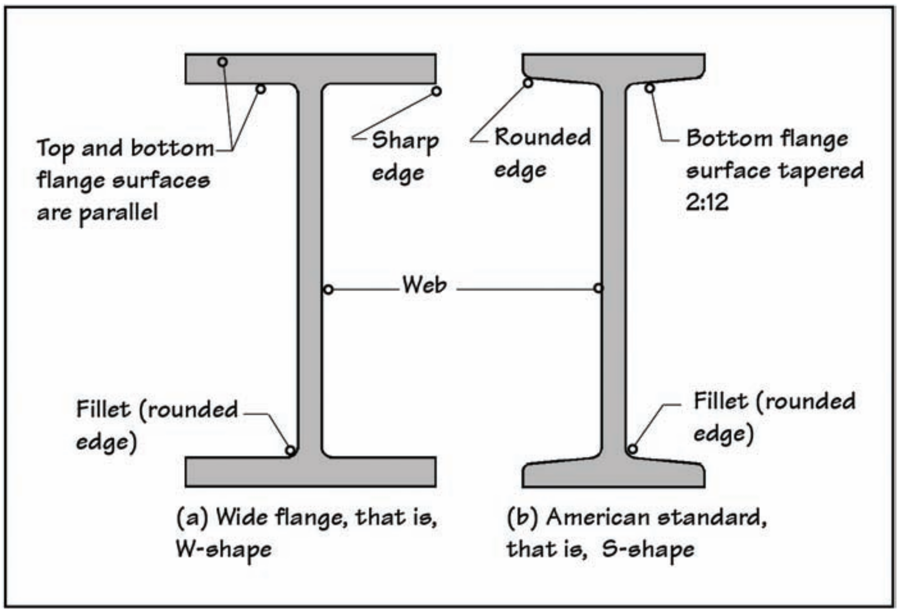

Top and bottom flange surfaces are parallel
Sharp edge
Rounded edge
Bottom flange surface tapered 2:12
Web
Fillet (rounded edge)
Fillet (rounded edge)
(a) Wide flange, that is, W-shape
(b) American standard, that is, S-shape

FIGURE 18.13 Comparison between W-shaped and S-shaped sections.

The interior flange-to-flange dimensions of most W-shapes sharing the same nominal depth designation are equal. For example, as shown in Figure 18.14, W14 × 132, W14 × 82, and W14 × 53 have two-dimensional facts in common: (a) their interior flange-to-flange dimension is the same (12.60 in.) and (b) their overall depths are approximately 14 in. All other dimensions of these sections are different from each other. Generally, W-shapes with squarish proportions (depth and flange width nearly equal), such as W14 × 132, are used as columns. Tall, narrow sections, such as W14 × 53, are used as beams.

An HP-shape is so called because it is generally used as a bearing pile (see Sections 11.6 and 12.3) and is squarish in proportion; that is, its overall depth and flange width are nearly equal, resembling the letter *H*. The thickness of the web and flanges are equal in an HP-shape. An M-shape is one that cannot be classified as W, S, or HP; the letter *M* is an acronym for *miscellaneous*.

Dimensional information and engineering properties of various structural steel shapes are available in the *Steel Construction Manual* published by the American Institute of Steel Construction (AISC). Table 18.1 gives an indication of some of the information available in this publication.

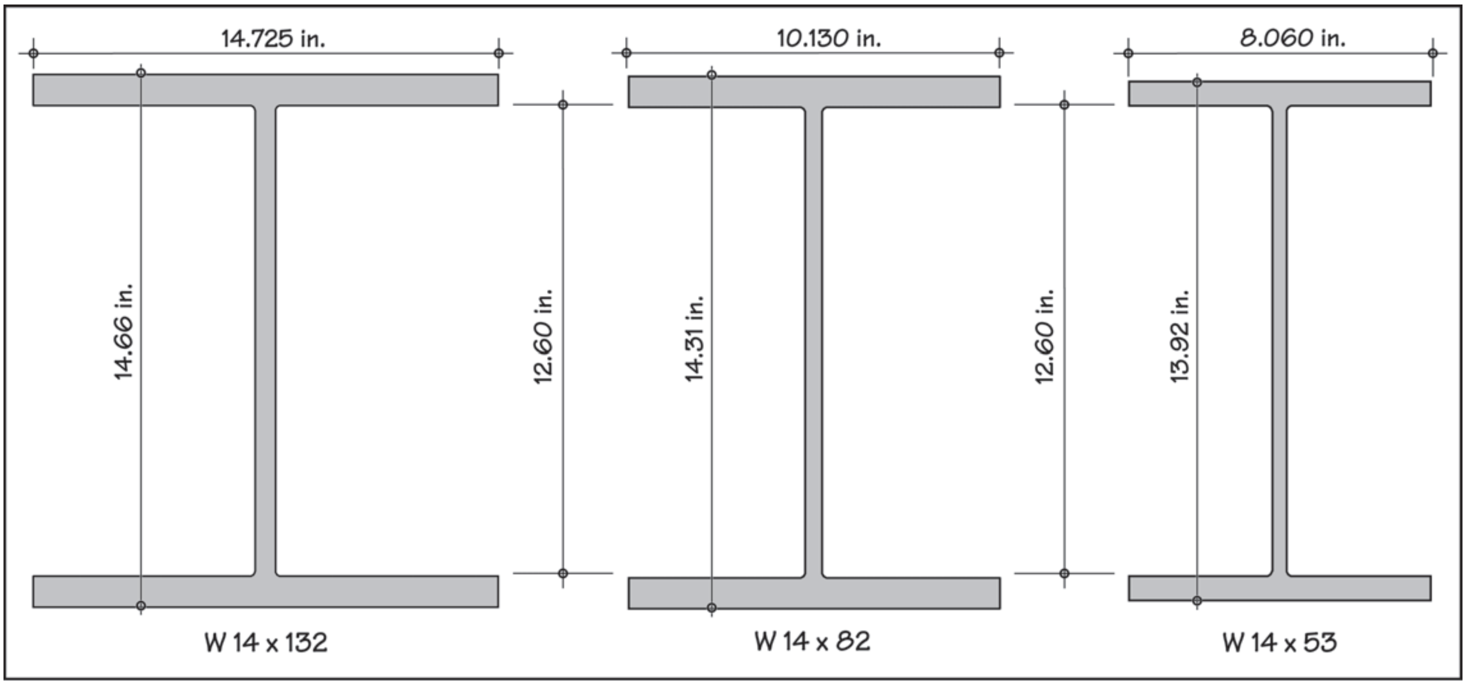
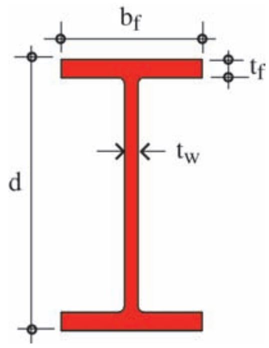

14.725 in.
10.130 in.
8.060 in.
14.66 in.
12.60 in.
14.31 in.
12.60 in.
13.92 in.
W 14 x 132
W 14 x 82
W 14 x 53

FIGURE 18.14 Most wide-flange sections that share a common nominal depth designation have the same interior flange-to-flange dimension. This illustration shows three sections, all with a nominal depth of 14 in. Their overall depths are nearly 14 in., and several other dimensions are different from each other. However, the interior flange-to-flange dimensions are 12.60 in. for all sections. Several other sections with a nominal depth of 14 in. are available (see Table 18.1).

TABLE 18.1 DIMENSIONAL INFORMATION ABOUT SELECTED W-SHAPES



W-Shape Dimensions

			Web	Flange	
	Area A	Depth d	Thickness t_w	Width b_f	Thickness t_f
Designation	in.^{2}	in.	in.	in.	in.
W14 × 132	38.8	14.66	0.645	14.725	1.030
×120	35.3	14.48	0.590	14.670	0.940
×109	32.0	14.32	0.525	14.605	0.860
×99	29.1	14.16	0.485	14.565	0.780
×90	26.5	14.02	0.440	14.520	0.710
W14 × 82	24.1	14.31	0.510	10.130	0.855
×74	21.8	14.17	0.450	10.070	0.785
×68	20.0	14.04	0.415	10.035	0.720
×61	17.9	13.89	0.375	9.995	0.645
W14 × 53	25.6	13.92	0.370	8.060	0.660
×48	14.1	13.79	0.340	8.030	0.595
×43	12.6	13.66	0.305	7.995	0.530
W14 × 38	21.2	14.10	0.310	6.770	0.515
×34	10.0	13.98	0.285	6.745	0.455
×30	8.85	13.84	0.270	6.730	0.385

Source: This table has been adapted from Steel Construction Manual (13th ed.), published by the American Institute of Steel Construction (AISC), with permission.

The table is an abridged version. A complete version includes additional dimensions and information about the engineering properties of each section, such as the moment of inertia, radius of gyration, and so on.

C-SHAPES

Steel channels (C-shapes) are similar in profile to S-shapes, that is, their inner flange surfaces are inclined at an angle of 2:12, Figure 18.15(a). They are designated by two numbers after the letter C. The first number gives the overall depth of the section, and the second number gives the weight of a 1-ft length of the section. Thus, C8 × 11.5 means that the channel is 8 in. deep and weighs 11.5 lb/ft.

Miscellaneous channels do not have a standard slope on the inner flange surfaces. They are designated in the same way as C-shapes, for example, MC12 × 50.

T-SHAPES

A T-shape section is made by splitting a W-shape, M-shape, or S-shape into two equal parts, Figure 18.15(b). It is, therefore, called WT, MT, or ST, depending on its origin. For example, two WT6 × 29 sections are obtained from one W12 × 58.

L-SHAPES, PIPES, TUBES, BARS, AND PLATES

Steel angles (L-shapes) may either be equal-leg angles or unequal-leg angles, Figure 18.15(c). The thickness of both legs is the same in an angle. Angles are designated by three numbers. The first two numbers give the length of each leg, and the third number gives the thickness

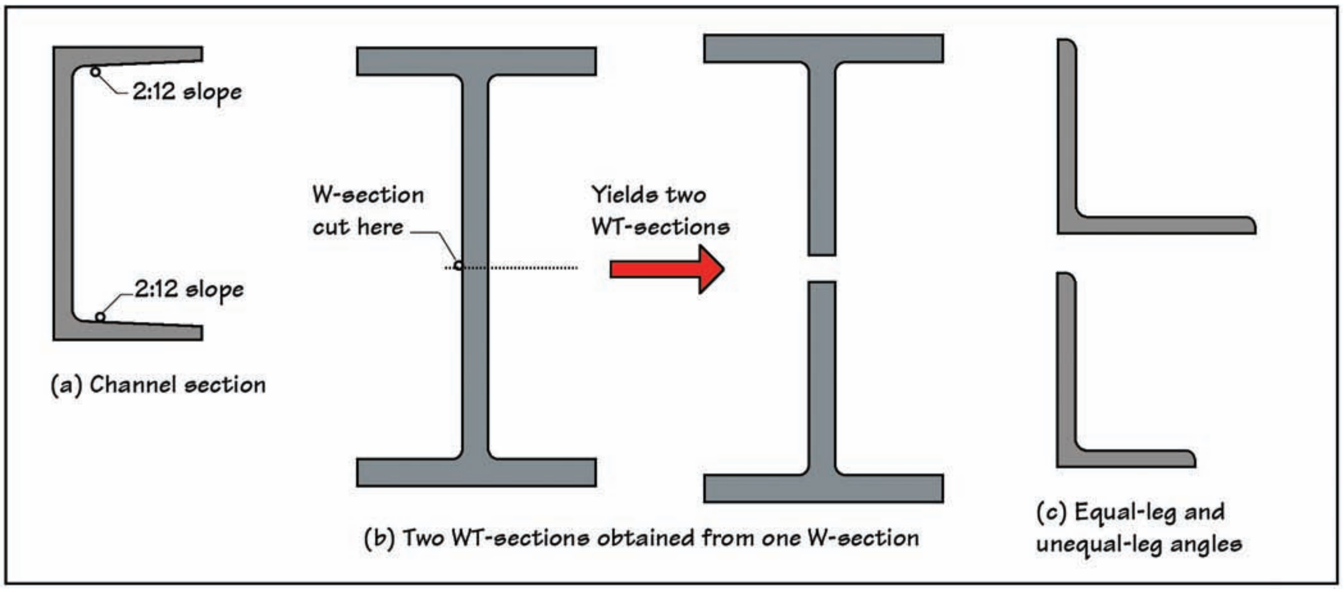


FIGURE 18.15 **(a)** Channel section profile, **(b)** WT-sections obtained from a W-section, **(c)** Equal-leg and unequal-leg angles.

of the legs. L4 × 4 × $\frac{1}{2}$ is an example of an equal-leg angle with legs equal to 4 in. each; the thickness of each leg is $\frac{1}{2}$ in. In an unequal-leg angle, the longer leg is mentioned first, as in L4 × 3 × $\frac{1}{4}$. Angles have various uses, such as for masonry lintels and members of steel trusses.

Pipes are designated by their nominal diameter and by whether the pipe is a *standard weight*, *extra strong*, or *double-extra strong*. These three designations refer to the pipe's wall thickness. Pipes are generally used as columns or as members of a truss.

A tube is referred to as a *hollow structural section* (HSS) and is made by bending a steel plate and welding it seamlessly. That is why the edges of a tube are rounded (Figure 18.10). An HSS may be square, rectangular, or round. Square or round HSSs are generally used as columns, and rectangular HSSs are used as beams. Like pipe trusses, HSS member trusses are fairly common for long-span structures.

A rectangular or square HSS member is designated by three dimensions, all expressed in fractional numbers. Thus, an HSS 12 × 8 × $\frac{1}{2}$ is a rectangular HSS measuring 12 in. × 8 in. on the outside; the wall thickness is $\frac{1}{2}$ in. A round HSS is designated by the outside diameter and wall thickness, both dimensions expressed to three decimal places. Thus, an HSS 10.000 × 0.500 has an outer diameter of 10 in. and a wall thickness of $\frac{1}{2}$ in.

BENT-PLATE SECTIONS AND BUILT-UP SECTIONS

When size and other requirements dictate the use of nonstandard shapes and (or) cross-sectional dimensions, they can be obtained by (a) bending a steel plate to the required profile, called *bent-plate sections* or (b) welding two or more standard sections together, called *built-up sections*. The most commonly used bent-plate profile is an angle. Bent-plate angles have a rounded corner, whereas a standard-size (hot-rolled) angle has a sharp corner, Figure 18.16(a). Bent-plate angles are used where an angle with odd dimensions (not available as a standard angle) is mandated by the detail (see Figure 28.33). A few examples of built-up sections are shown in Figure 18.16(b).

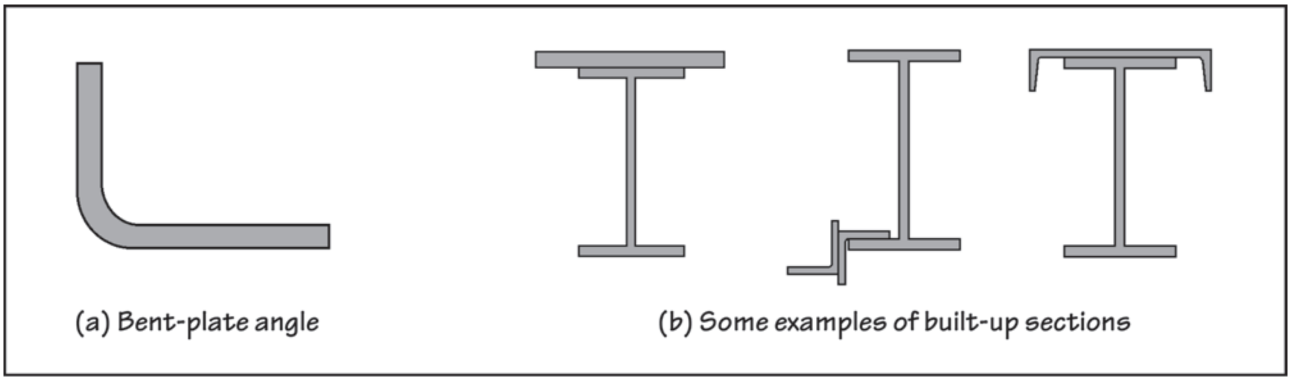
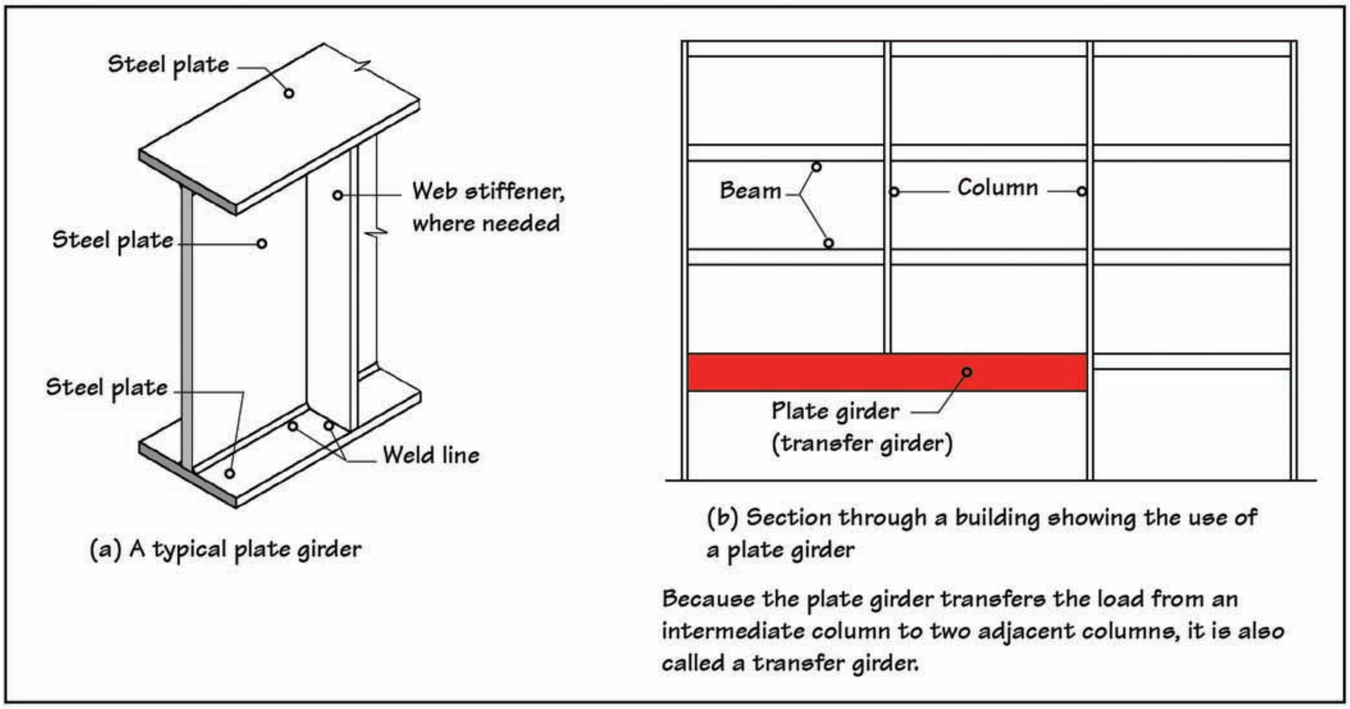


FIGURE 18.16 Bent-plate angle and built-up sections.

In some situations, it is necessary to use a W-shape beam that is deeper than the deepest (44 in.) W-shape available. Such a built-up beam can be obtained by welding steel plates together, Figure 18.17(a). Because the beam is fabricated from plates, it is also called a *plate girder*. Plate girders are fairly common in bridge structures. In buildings, they are employed to carry heavy loads over long spans, such as to support the weight of columns that must be omitted at the lower levels to achieve a larger unobstructed space, Figure 18.17(b).



(a) A typical plate girder

(b) Section through a building showing the use of a plate girder

Because the plate girder transfers the load from an intermediate column to two adjacent columns, it is also called a transfer girder.

FIGURE 18.17 **(a)** Anatomy of a typical plate girder. **(b)** One of the several uses of a plate girder.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. Which of the following ferrous metals has the largest amount of carbon?
   - **a.** Steel
   - **b.** Wrought iron
   - **c.** Cast iron
2. Which of the following ferrous metals is least corrosion resistant?
   - **a.** Steel
   - **b.** Wrought iron
   - **c.** Cast iron
3. An integrated mill produces steel using
   - **a.** steel scrap.
   - **b.** iron ore.
   - **c.** 25% to 50% iron ore plus 25% to 50% scrap.
   - **d.** none of the above.
4. The mini-mill method of steel manufacturing predates the integrated-mill method.
   - **a.** True
   - **b.** False
5. An electric arc furnace uses
   - **a.** two electrodes to melt iron ore.
   - **b.** two electrodes to melt steel scrap.
   - **c.** three electrodes to melt iron ore.
   - **d.** three electrodes to melt steel scrap.
   - **e.** none of the above.
6. Slag is
   - **a.** a waste product generated from the manufacture of steel.
   - **b.** the ore used for making steel.
   - **c.** the ore used for making aluminum.
   - **d.** a ferrous metal that has been replaced by steel.
   - **e.** none of the above.
7. When steel structures first appeared, they were called
   - **a.** skeleton frame.
   - **b.** skeleton cage.
   - **c.** steel skeleton.
   - **d.** all of the above.
   - **e.** none of the above.
8. Which of the following statements is true?
   - **a.** All structural steel sections are made from billets or blooms that are rolled to shape at room temperature.
   - **b.** All structural steel sections are made by preheating steel sheets and bending them to the required cross sections.
   - **c.** All structural steel sections are made by bending steel sheets to the required cross sections at room temperature.
   - **d.** All structural steel sections are made by preheating billets or blooms and rolling them to shape.
   - **e.** none of the above.
9. Steel decks are made from cold-formed steel.
   - **a.** True
   - **b.** False
10. The steel type most commonly used for framing members (columns and beams) of a steel building is
    - **a.** steel type A36 with a yield strength of 36 ksi.
    - **b.** steel type A36 with a yield strength of 360 ksi.
    - **c.** steel type A992 with a yield strength of 50 ksi.
    - **d.** steel type A992 with a yield strength of 40 ksi.
    - **e.** none of the above.

PRACTICE QUIZ *(Continued)*

11. A W-shape section is so called because
  a. it is an I-section with wide flanges.
  b. it is an I-section with a wide web.
  c. its cross-sectional shape resembles the letter *W*.
  d. it is a rectangular section whose width is larger than its depth.

12. W-shape, S-shape, HP-shape, and M-shape are all structural steel I-sections.
  a. True **b.** False

13. Which of the following steel shapes is most commonly used for the structural frame of buildings?
  a. HP-shape **b.** S-shape
  c. M-shape **d.** W-shape
  e. C-shape

14. The designation W14 × 38 means that the
  a. width of the section is 14 in. and the depth is 38 in.
  b. depth of the section is 14 in. and the width is 38 in.
  c. depth of the section is 14 in. and its weight is 38 lb/ft.
  d. nominal depth of the section is 14 in. and its weight is 38 lb/ft.
  e. none of the above.

15. To obtain the structural engineering properties of standard steel sections, the following publication is generally used.
  a. *Steel Fabricators' Manual*
  b. *Steel Construction Manual*
  c. ASTM standard on steel sections
  d. Local manufacturers' literature
  e. *Steel Erectors' Manual*

16. In a steel angle, both legs must have the same thickness but may be of different lengths.
  a. True **b.** False

17. The acronym HSS stands for
  a. heat-strengthened steel.
  b. high-strength steel.
  c. high-strength section.
  d. hollow steel section.
  e. none of the above.

18. HSS members are made by
  a. bending and welding heated steel plates.
  b. cold rolling of steel blooms.
  c. hot rolling of steel blooms.
  d. casting molten steel to shape.
  e. any one of the above, depending on the manufacturer.

18.5 STEEL JOISTS AND JOIST GIRDERS—FROM HOT-ROLLED SECTIONS

In addition to the standard steel shapes and built-up sections, two types of prefabricated steel members are commonly used for roof and floor structures in buildings. These are trusslike, open-web members, called *joists* and *joist girders*. There is no fundamental difference between a joist and a joist girder, except that a joist girder is a heavier member and spans from column to column, whereas a joist is a lighter member that spans between the girders, Figure 18.18.

Joists and joist girders are fabricated by manufacturers according to the specifications prepared by the Steel Joist Institute (SJI). They are generally recommended for use in light, uniformly loaded roofs and floors.

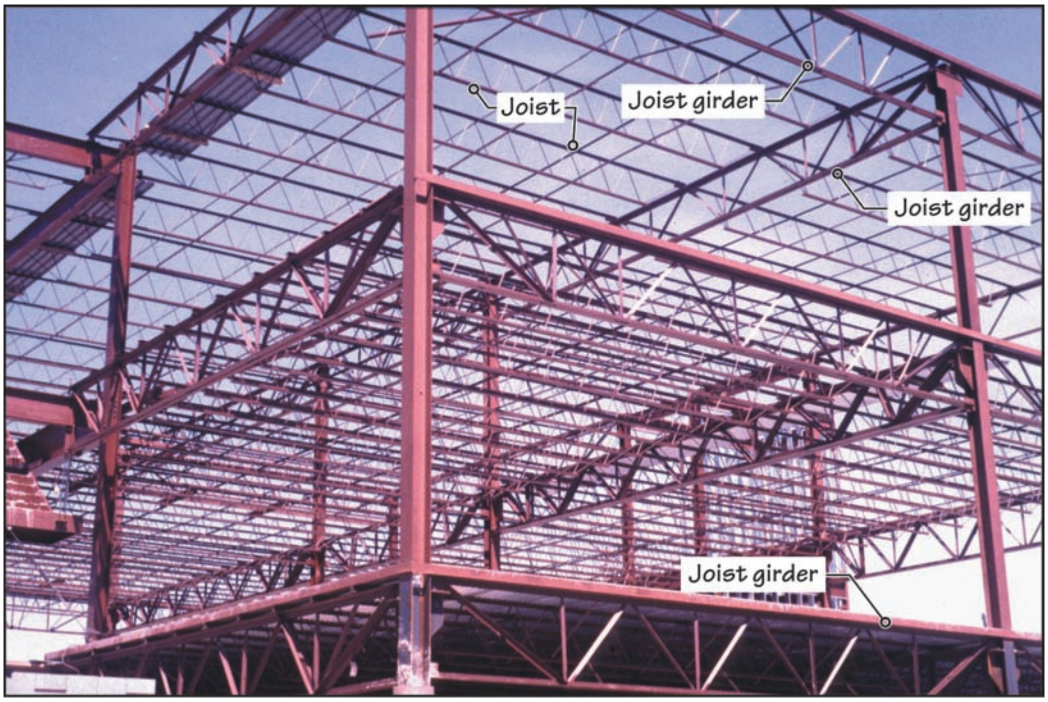


FIGURE 18.18 A steel frame structure showing the use of steel joists and steel joist girders. Observe that a joist girder spans from column to column. A joist, on the other hand, spans from joist girder to joist girder. A joist bears on a girder only through its top chord; the bottom chord of the joist is free (see Figures 18.19(e) and (f)). Both the top and bottom chords of a joist girder, on the other hand, are connected to the columns at both ends—a connection that provides lateral stability to the structure (i.e., resistance to lateral loads).

NOTE

Joist Series' Nomenclature

Until 1986, SJI had three series of joists: H-series, LH-series, and DLH-series. H-series joists (ranging from 8 to 30 in. deep) were most frequently used because their depths and load-carrying capacities were within the range commonly required. LH-series and DLH-series joists, referred to as *long-span* and *deep long-span* joists, respectively, were intended for spans and loads not covered by H-series joists.

In 1986, SJI introduced K-series joists, which replaced the earlier H-series joists primarily because of the savings resulting from the improved design concepts.

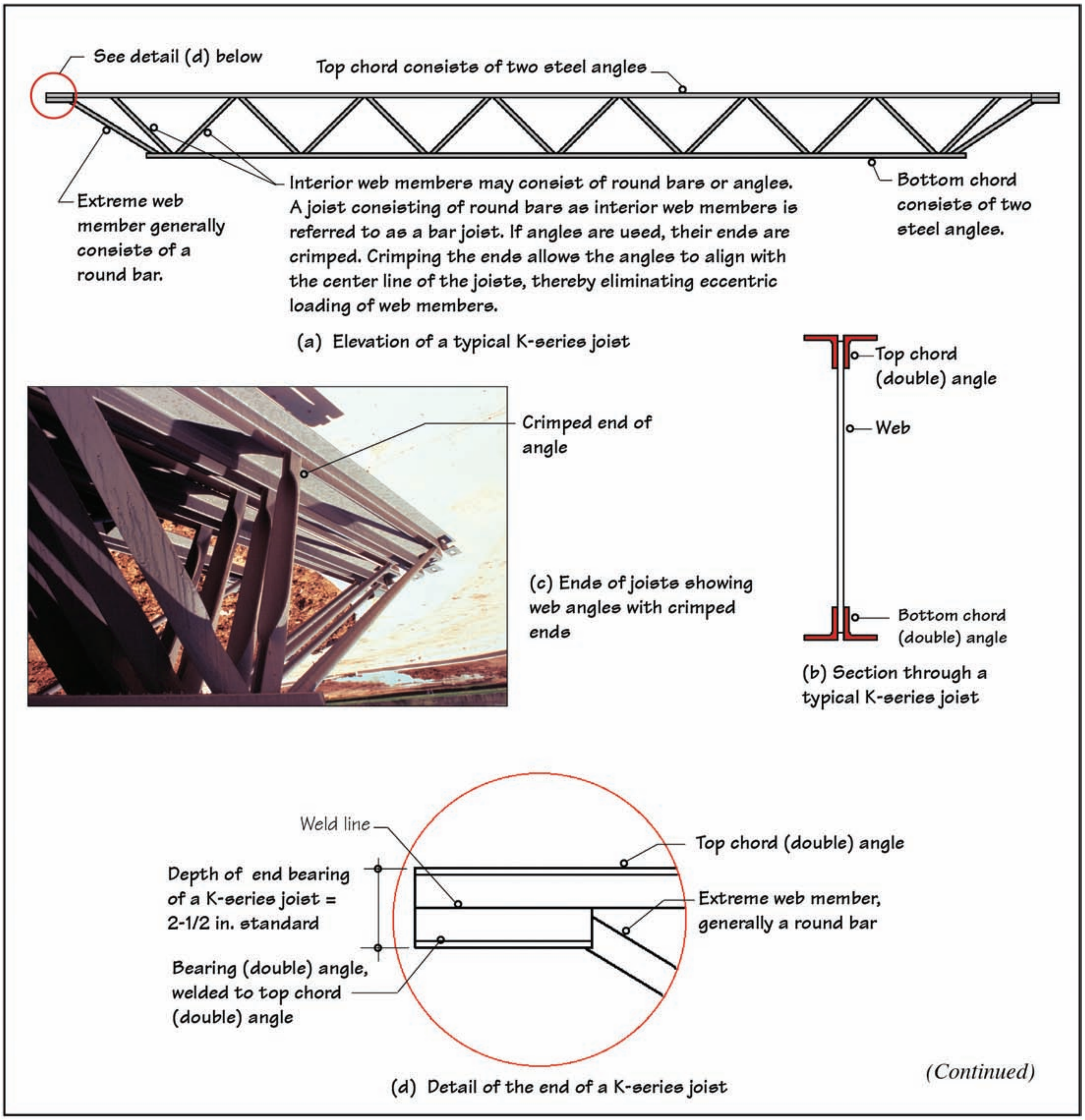
STEEL JOISTS

The Steel Joist Institute (SJI) classifies joists into three categories:

- K-series joists (joist depth ranges from 8 in. to 30 in.)
- LH-series joists (joist depth ranges from 18 in. to 48 in.)
- DLH-series (joist depth ranges from 52 in. to 72 in.)

K-series joists are more frequently used because they fall within the range of loads and spans that are common in buildings. Manufacturers producing K-series joists must comply with SJI's specifications, which, for the most part, are performance-oriented, giving a measure of freedom to manufacturers to select the members' sizes and shapes. However, a joist bearing the standard SJI designation must have a minimum specified load-carrying capacity.

Figure 18.19 shows a typical elevation, section, and other important details of a K-series joist. Each joist bears a designation, consisting of two numbers sandwiching the letter *K*. The first number gives the depth of joists in inches, and


See detail (d) below
Top chord consists of two steel angles
Extreme web member generally consists of a round bar.
Interior web members may consist of round bars or angles. A joist consisting of round bars as interior web members is referred to as a bar joist. If angles are used, their ends are crimped. Crimping the ends allows the angles to align with the center line of the joists, thereby eliminating eccentric loading of web members.
Bottom chord consists of two steel angles.
Top chord (double) angle
Web
Bottom chord (double) angle
Crimped end of angle
Weld line
Depth of end bearing of a K-series joist = 2-1/2 in. standard
Bearing (double) angle, welded to top chord (double) angle
Top chord (double) angle
Extreme web member, generally a round bar

(a) Elevation of a typical K-series joist

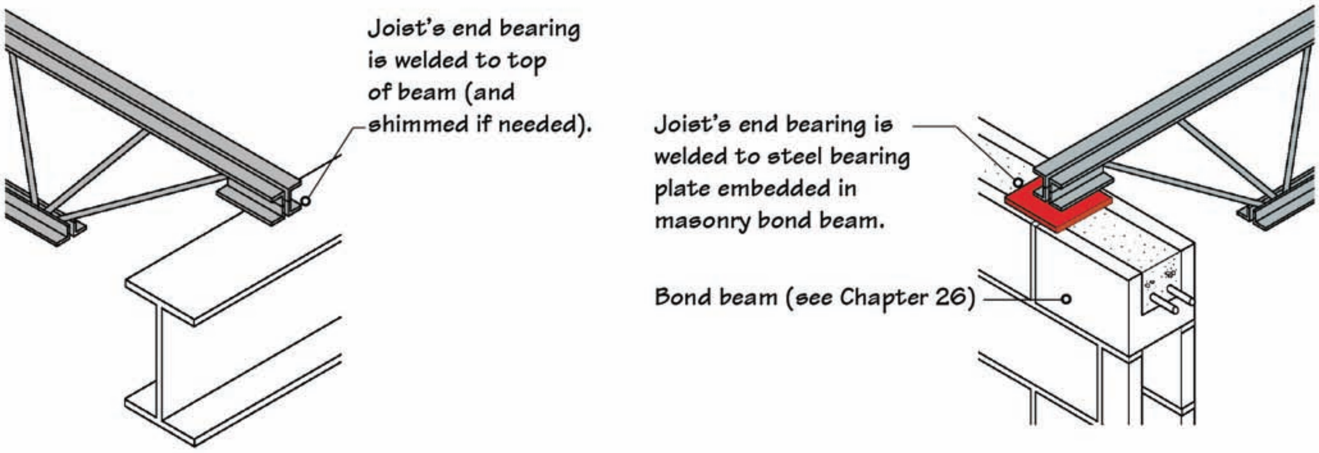
(b) Section through a typical K-series joist

(c) Ends of joists showing web angles with crimped ends

(d) Detail of the end of a K-series joist

(Continued)

FIGURE 18.19 Essential details of K-series joists.


Joist's end bearing is welded to top of beam (and shimmed if needed).
Joist's end bearing is welded to steel bearing plate embedded in masonry bond beam.
Bond beam (see Chapter 26)

(e) Support detail of a K-series joist bearing on a wide-flange beam. Bearing of a joist on joist girder is similar.

(f) Support detail of a K-series joist bearing on a masonry wall. Detail of joist bearing on a reinforced concrete wall is similar.

K-SERIES JOIST DESIGNATION

K-series joists are designated by two numbers one on each side of letter "K". The left side number gives the depth of the joist in inches and varies from 8 to 30 in 2 in.-increments, that is, the left side numbers can be 8, 10, 12, ..., 30. Thus, the minimum depth of a K-series joist is 8 in. and the maximum depth is 30 in. For example, the depth of joist, designated as 16K4, is 16 in.

The right side number gives the relative weight of the joist and varies from 1 to 12 in steps of 1, that is, the right side numbers can be 1, 2, 3, ..., 12. For the same joist depth, the larger the right side number, the heavier the joist. Thus, a 16K5 joist is heavier (and, therefore, being of the same depth is stiffer) than a 16K4 joist and has a greater load-carrying capacity.

HEIGHT OF END BEARING OF K-SERIES JOISTS

The height and depth of end bearing is 2-1/2 in. for all K-series joists.

TYPICAL SPACING OF K-SERIES JOISTS

Joist spacing must be determined by the engineer or architect depending on the load-carrying capacity of floor or roof deck. It generally varies from 2 ft to 4 ft for floors and 4 ft to 6 ft for roofs.

MAXIMUM SPAN OF K-SERIES JOISTS

As Table 18.2 shows, the maximum allowable span of a joist is 24 times its depth. Thus, a 10-in.-deep joist can be used for a maximum span of 240 in. = 20 ft.

FIGURE 18.19 (*continued*) Essential details of K-series joists.

the second number gives the relative stiffness of the joist. The designation system is further explained in Figure 18.19.

The load-carrying capacities of various K-series joists are tabulated as shown in Table 18.2. Thus, in practice, the joists are not structurally designed but are simply selected from SJI's load tables based on the dead load and live load that they are required to support.

LH- and DLH-series joists are designated similarly to K-series joists, for example, 24LH10 and 56DLH16. The maximum allowable span of a given joist (regardless of the joist series) is 24 times the depth of the joist. For example, the maximum allowable span of joists designated as 24K4, 24K5, 24K6, and so on, is 48 ft.

STEEL JOIST GIRDERS

As shown in Figure 18.18, joist girders are used as primary structural elements as an economical alternative to W-shape beams. Unlike the joists, which are selected from standard SJI load tables, joist girders are designed by the manufacturers based on the specifications provided by the engineer.

BRACING JOISTS AND JOIST GIRDERS AGAINST INSTABILITY

Steel joists and joist girders are slender elements and are, therefore, unstable and prone to overturning. As per SJI's specifications, the joists must be stabilized by rows of continuous

TABLE 18.2 STANDARD LOAD TABLE OF SELECTED K-SERIES JOISTS

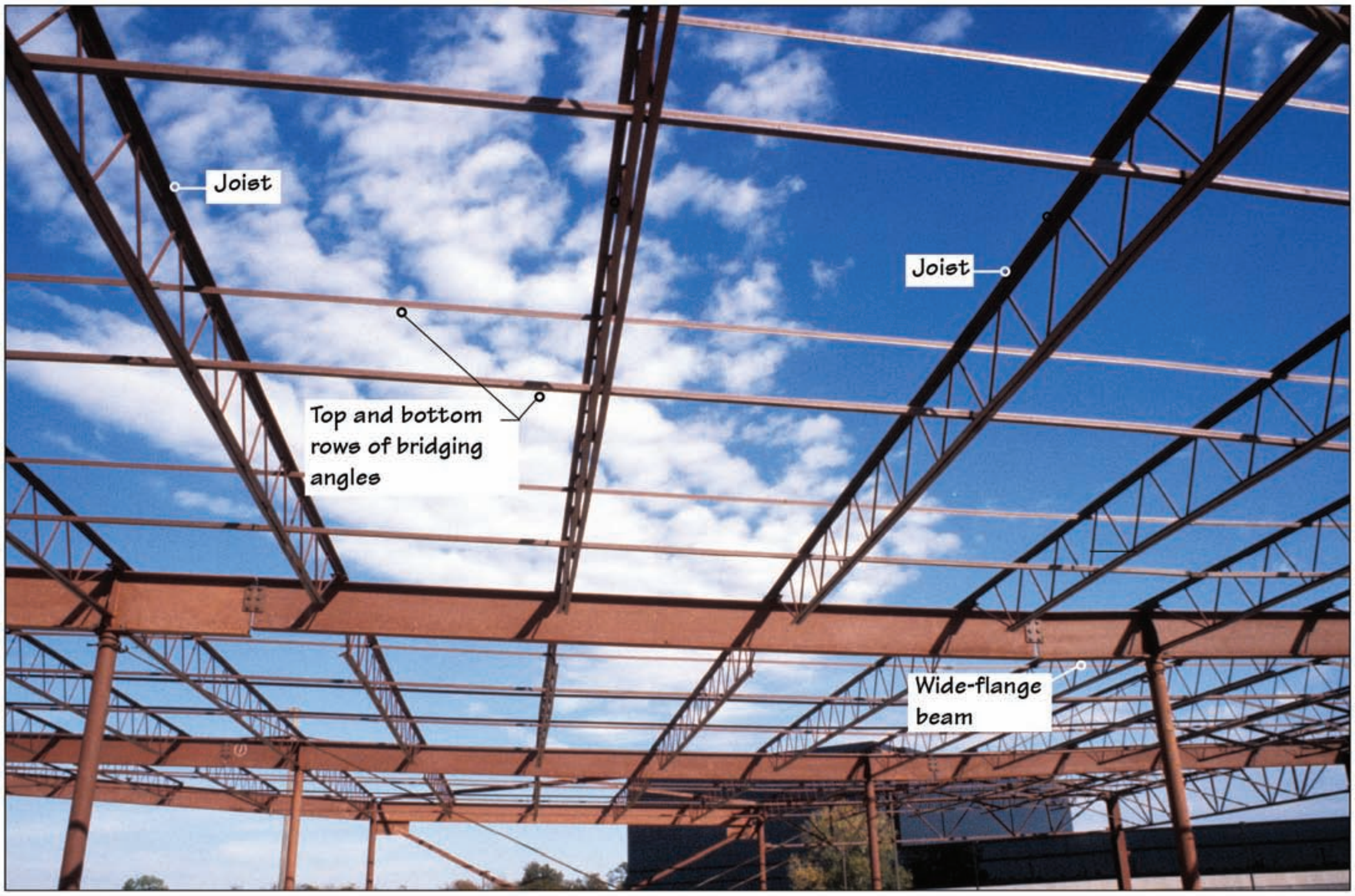
Joist Designation	**8K1**	**10K1**	**12K1**	**12K3**	**12K5**	**14K1**	**14K3**	**14K4**	**14K6**
Depth (in.)	**8**	**10**	**12**	**12**	**12**	**14**	**14**	**14**	**14**
Approx. weight (lb/ft)	**5.1**	**5.0**	**5.0**	**5.7**	**7.1**	**5.2**	**6.0**	**6.7**	**7.7**
Span (ft)									
8	550								
	550								
9	550								
	550								
10	550	550							
	480	550							
11	532	550							
	377	**542**							
12	444	550	550	550	550				
	288	**455**	**550**	**550**	**550**				
13	377	479	550	550	550				
	225	**363**	**510**	**510**	**510**				
14	324	412	500	550	550	550	550	550	550
	179	**289**	**425**	**463**	**463**	**550**	**550**	**550**	**550**
15	281	358	434	543	550	511	550	550	550
	145	**234**	**344**	**428**	**434**	**475**	**507**	**507**	**507**
16	246	313	380	476	550	448	550	550	550
	119	**192**	**282**	**351**	**396**	**390**	**467**	**467**	**467**
17		277	336	420	550	395	495	550	550
		159	**234**	**291**	**366**	**324**	**404**	**443**	**443**
18		246	299	374	507	352	441	530	550
		134	**197**	**245**	**317**	**272**	**339**	**397**	**408**
19		221	268	335	454	315	395	475	550
		113	**167**	**207**	**269**	**230**	**287**	**336**	**383**
20		199	241	302	409	284	356	428	525
		97	**142**	**177**	**230**	**197**	**246**	**287**	**347**
21			218	273	370	257	322	388	475
			123	**153**	**198**	**170**	**212**	**248**	**299**
22			199	249	337	234	293	353	432
			106	**132**	**172**	**147**	**184**	**215**	**259**
23			181	227	308	214	268	322	395
			93	**116**	**150**	**128**	**160**	**188**	**226**
24			166	208	282	196	245	295	362
			81	**101**	**132**	**113**	**141**	**165**	**199**
25						180	226	272	334
						100	**124**	**145**	**175**
26						166	209	251	308
						88	**110**	**129**	**156**
27						154	193	233	285
						79	**98**	**115**	**139**
28						143	180	216	265
						70	**88**	**103**	**124**

Note: The normal-weight numbers represent the total safe, uniform load-carrying capacity of joists in pounds per foot. Dead loads, including the self-load of joists, must be deducted to determine the joist's live-load capacity. Boldface numbers represent the live load (in pounds per foot) that will produce a deflection in the joist equal to the joist span divided by 360.

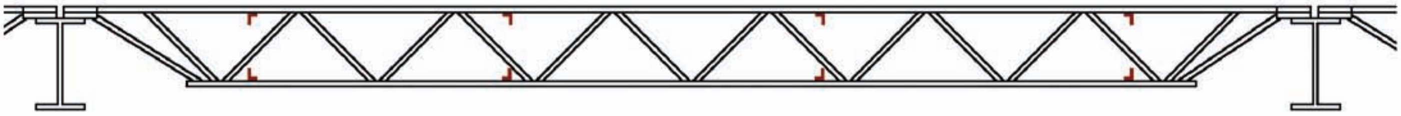
Source: Adapted from 42nd Edition Standard Specifications Load Tables and Weight Tables for Steel Joists and Joist Girders. Published by Steel Joist Institute © 2005.

horizontal members, referred to as *horizontal bridging members*. Horizontal bridging members are used in rows: One row is welded to the top chord of the joist, and the other row is welded to the bottom chord, Figure 18.20.

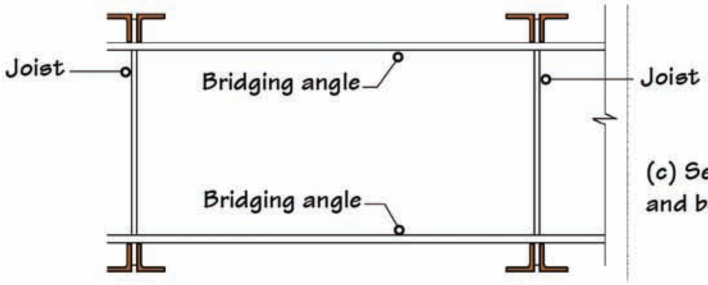
Generally, the bridging members are $1\frac{1}{4}$ in. × $1\frac{1}{4}$ in. angles, but they must meet the stiffness and strength requirements of SJI's specifications. An alternative to horizontal bridging is *diagonal bridging*, as shown in Figure 18.21. Regardless of which bridging alternative is



(a) Steel frame structure with wide-flange beams as primary structural elements and steel joists as secondary elements. The steel deck (not shown here) forms the tertiary element—the three elements together typically comprise the floor or the roof structure in a steel frame building. In Figure 18.18, the primary floor elements are the joist girders. In many steel frame buildings, wide-flange beams comprise both primary and secondary elements of the floor.



(b) Elevation of a steel joist with top and bottom rows of bridging angles (shown in red). Note that the joist bears on a W-shape beam at each end.



(c) Section through steel joists with top and bottom bridging angles

FIGURE 18.20 Horizontal bridging of steel joists to provide stability against overturning.

used, it is important that the end spans of the bridging are securely connected to the wall or spandrel beam. The spacing between the rows of bridging is also specified by SJI. Bridging is particularly important in roofs to prevent the buckling of a joist's bottom chord that comes under compression due to the uplift from the wind loads on the roof.

Unlike joists, joist girders are stabilized by connecting their lower chords to the columns (see Figure 18.18). This connection may also be designed to provide lateral-load (racking) resistance to the structural frame of the building.

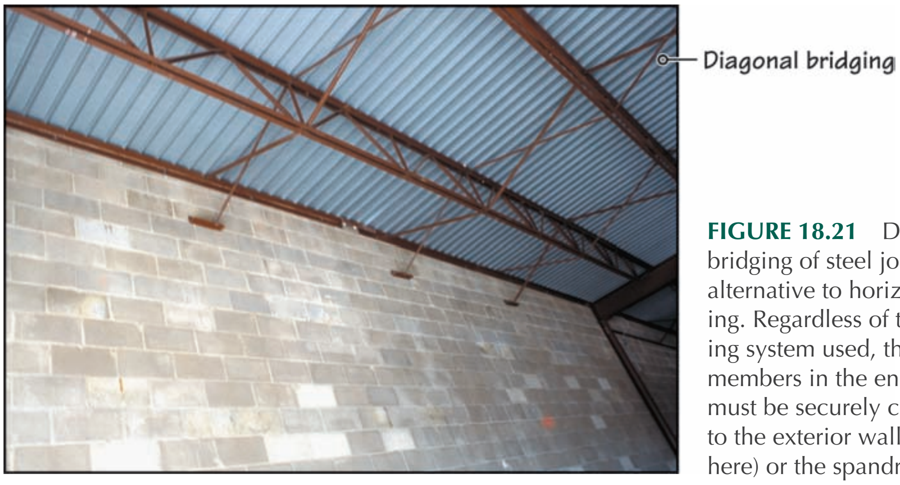


FIGURE 18.21 Diagonal bridging of steel joists is an alternative to horizontal bridging. Regardless of the bridging system used, the bridging members in the end spans must be securely connected to the exterior wall (as shown here) or the spandrel beam.

EXPAND YOUR KNOWLEDGE

Steel Joists and Joist Girders Compared With W-Shapes

Advantages of Steel Joists and Joist Girders

Lighter Weight
Compared with W-shape beams, steel joists and joist girders are generally an economical alternative for roof and floor structures. The reason is that for a given span and floor/roof loads, the structural solution based on the use of joists and joist girders is lighter in weight than that obtained by using W-shape beams. A lighter-weight floor/roof structure reduces not only its own cost, but also the cost of columns and foundations.

Easier Erection
Because of their bearing-type support, steel joists are much easier and faster to erect and install than W-shape beams. W-shape beams use shear connections, which are more complex and take longer to erect. Joists also allow panelized erection, in which a number of parallel joists can be connected together with bridging members and decking and the entire assembly lifted into position.

Limitations of Steel Joists and Joist Girders

Greater Floor-to-Floor Height
The depth of a floor using W-shapes is generally smaller than that using steel joists. This is particularly helpful in a high-rise building, where even a small reduction in floor-to-floor height can translate into a substantial decrease in the overall height of the building and, hence, in the magnitude of lateral loads.

However, the open webs of steel joists allow the passage of electrical conduits, pipes, and air-conditioning ducts within the depth of the floor. Thus, although the depth of the floor using joists and joist girders may be greater than that using W-shape beams, the floor-to-floor height may not be. (Because of their open webs, joists and joist girders are also referred to as *open-web joists* and *open-web joist girders*.)

Concentrated Loads
Although joists can be designed to support concentrated loads, they are less forgiving than W-shape beams if the location of a concentrated load changes from its designed location. Joist girders, on the other hand, are required to support concentrated loads, particularly from the joists bearing on them.

Complex Layout of Floor and Roof Framing
Steel joists are economical for a floor or roof that is rectangular in plan, so that the layout of joists is uniform and rhythmic. They are generally not economical for a floor or roof that has nonrectangular bays with different spans for adjacent joists.

Fire Protection
Steel joists are more closely spaced and have a greater surface area than W-shape beams. Therefore, they require a larger amount of spray-on fire-protection material.

NOTE

Nonstructural Concrete Fill on Roof Decks

Some roof decks are topped with lightweight insulating concrete instead of rigid board insulation (see Chapters 5 and 33).

18.6 STEEL ROOF AND FLOOR DECKS—COLD-FORMED STEEL

As stated in Section 18.3, steel decks are made from sheet steel by pressing the sheets into various cross-sectional profiles at room temperature, hence the term *cold-formed steel*. They are available in two categories: (a) *roof decks* and (b) *floor decks*. The primary difference between them is that a roof deck is generally topped with rigid insulation and a roofing membrane (for waterproofing), and a floor deck is topped with structural concrete fill. The terminology used to describe the deck profile is given in Figure 18.22.

The thickness of a sheet steel used in decks is expressed by its gauge number. The higher the gauge number, the thinner the sheet. Table 18.3 gives the U.S. Standard sheet-steel gauge number and the corresponding sheet thickness. Roof and floor decks are generally painted or galvanized for protection against corrosion.

ROOF DECKS

Commonly used steel roof decks profiles, depths, and gauges are shown in Figure 18.23. Roof decks ranging from $1\frac{1}{2}$ in. to $7\frac{1}{2}$ in. in depth are available. The greater the depth and the thicker the gauge, the greater the spanning capability of the deck.

TABLE 18.3 SHEET-STEEL GAUGE NUMBERS AND CORRESPONDING THICKNESSES AS USED IN ROOF AND FLOOR DECKS

	Thickness			Thickness	
Gauge number	**(in.)**	**(mm)**	**Gauge number**	**(in.)**	**(mm)**
14	0.0747	1.88	20	0.0359	0.89
15	0.0673	1.70	21	0.0329	0.82
16	0.0598	1.50	22	0.0299	0.75
17	0.0538	1.35	23	0.0269	0.67
18	0.0478	1.19	24	0.0239	0.60
19	0.0418	1.04	25	0.0209	0.52

Note: This is an incomplete table. Gauge numbers lower than 14 and higher than 25 are part of the complete table.

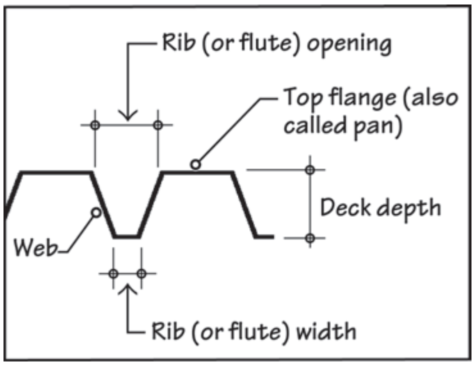
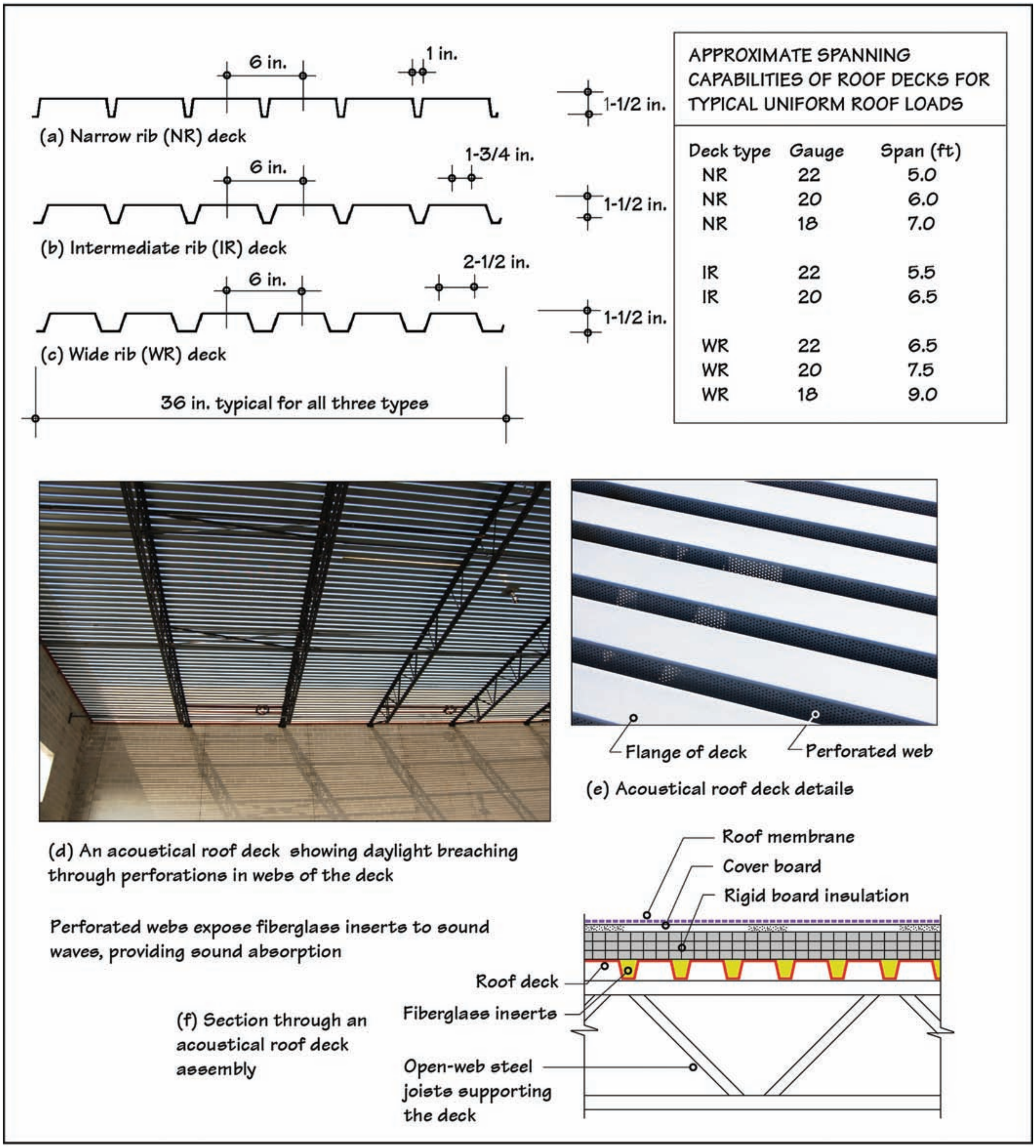

Rib (or flute) opening
Top flange (also called pan)
Deck depth
Web
Rib (or flute) width

FIGURE 18.22 Deck terminology.


6 in.
1 in.
1-1/2 in.
6 in.
1-3/4 in.
1-1/2 in.
6 in.
2-1/2 in.
1-1/2 in.
36 in. typical for all three types
Flange of deck
Perforated web
Roof membrane
Cover board
Rigid board insulation
Roof deck
Fiberglass inserts
Open-web steel joists supporting the deck

(a) Narrow rib (NR) deck

(b) Intermediate rib (IR) deck

(c) Wide rib (WR) deck

APPROXIMATE SPANNING CAPABILITIES OF ROOF DECKS FOR TYPICAL UNIFORM ROOF LOADS

Deck type	Gauge	Span (ft)
NR	22	5.0
NR	20	6.0
NR	18	7.0
IR	22	5.5
IR	20	6.5
WR	22	6.5
WR	20	7.5
WR	18	9.0

(d) An acoustical roof deck showing daylight breaching through perforations in webs of the deck

(e) Acoustical roof deck details

Perforated webs expose fiberglass inserts to sound waves, providing sound absorption

(f) Section through an acoustical roof deck assembly

FIGURE 18.23 Commonly used roof deck types.

Because of their extensive use, $1\frac{1}{2}$-in.-deep decks are available in three rib widths: narrow rib deck, intermediate rib deck, and wide rib deck. The wider the ribs, the greater the load-carrying capacity of the deck. Thus, for the same sheet thickness and deck depth, a wide rib deck has a greater load-carrying capacity than an intermediate rib deck, which in turn has a greater load-carrying capacity than a narrow rib deck.

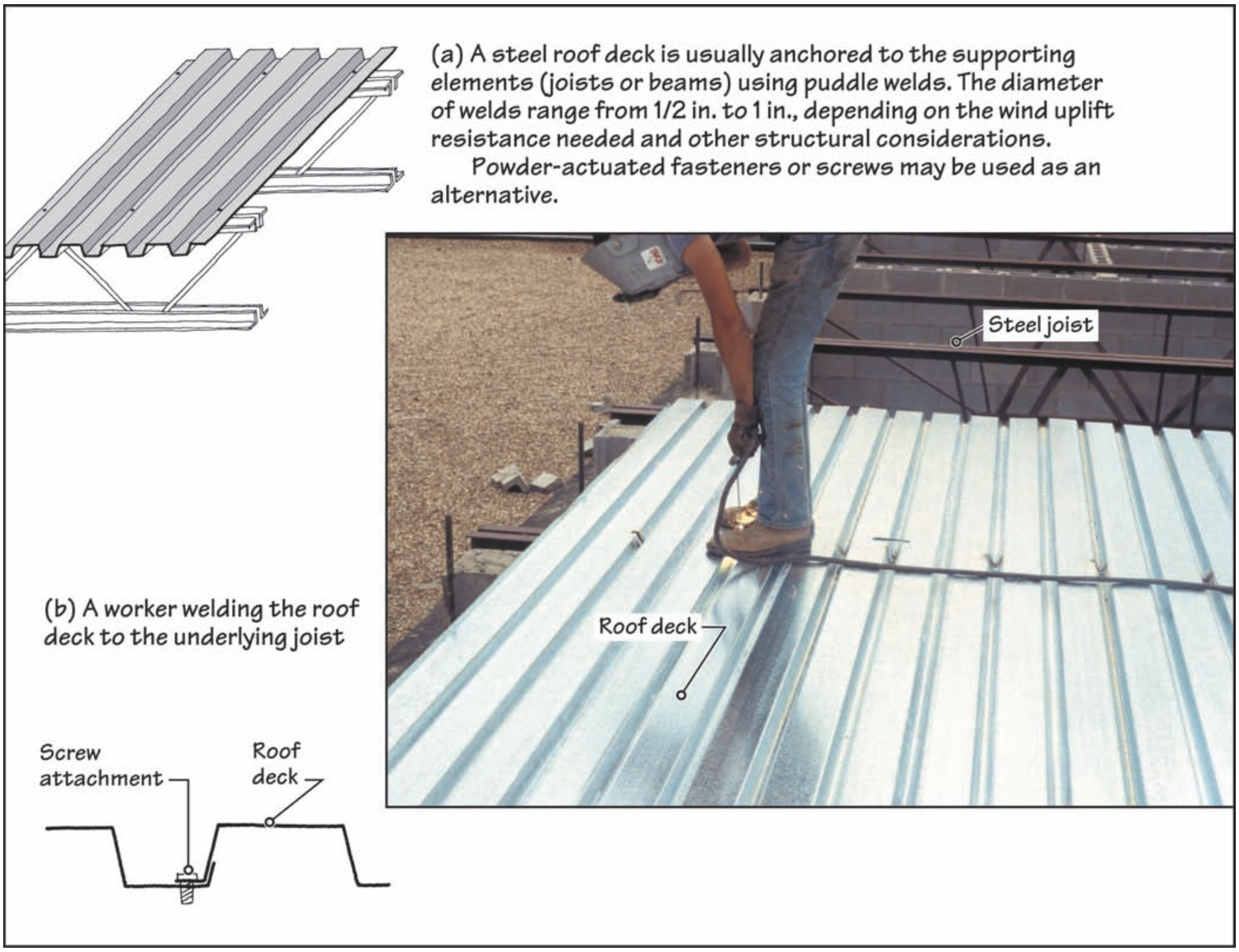
The width of a deck panel varies from 24 in. to 36 in., depending on the manufacturer and the type of deck. The length of the panel is usually not fixed, and the manufacturer generally provides whatever length is specified. However, there are practical limitations on panel length, determined by transportation constraints and the ability of workers to handle long panels at the job site. Panels longer than 40 ft (12 m) are cumbersome to handle.

Steel roof decks are commonly manufactured from 22-gauge to 18-gauge sheet steel. The fastener (weld) retention of a deck increases significantly with an increase in deck thickness. Because roof decks are subjected to wind uplift, the roof deck's gauge may be governed by wind-uplift considerations rather than its capacity to carry gravity loads.

Roof decks are available with a paint finish, hot-dip galvanized, or simply prime painted. Priming of the deck gives only temporary protection. In corrosive or high-moisture environments (e.g., coastal areas), galvanized or galvanized and painted decks should be used.

Roof decks are usually anchored to supporting elements (joists or wide-flange beams) by puddle (spot) welds, Figures 18.24(a) and (b). Weld areas are field painted. As an alternative to welding, powder-actuated fasteners or mechanical fasteners may be used.

Individual deck panels must be connected together at side laps, that is, along the length of the panel. This prevents differential deflection between adjacent panels and, therefore, prevents side joints from opening. Depending on the design of the deck profile, side-lap connection may be provided by screws or welds.



(a) A steel roof deck is usually anchored to the supporting elements (joists or beams) using puddle welds. The diameter of welds range from 1/2 in. to 1 in., depending on the wind uplift resistance needed and other structural considerations.

Powder-actuated fasteners or screws may be used as an alternative.

(b) A worker welding the roof deck to the underlying joist

FIGURE 18.24 Anchorage of a roof deck to supporting elements.

FLOOR DECKS

A steel floor deck functions as a working platform as well as permanent formwork for the concrete fill, so that the deck and the fill form a concrete floor slab. Two types of floor decks are used:

- A *form deck* functions as permanent formwork only. Thus, the concrete slab must be reinforced with conventional reinforcement, Figure 18.25.
- In a *composite deck*, the deck also functions as steel reinforcement for the concrete slab, reducing the need for conventional concrete reinforcing bars.

The surface of a composite floor deck is designed so that the deck bonds integrally with the overlying concrete fill. Protrusions and depressions are, therefore, stamped on the deck surface, Figure 18.26.

Because a composite deck provides permanent reinforcement, the deck must be protected from corrosion. Two alternatives are generally used. The better alternative is a hot-dip galvanized finish. Another alternative is a phosphatized/painted finish, in which the exposed deck surface is painted and the unexposed surface is phosphatized. The minimum concrete cover above the deck is 2 in. A composite deck is not recommended for use in parking garages in cold regions where salt spread is used on the roads.

Because a form deck supports only the weight of wet concrete (no floor live load) and does not function as concrete reinforcement, it is usually much shallower and of a thinner gauge than a composite deck. A composite deck, on the other hand, must support the dead load of wet concrete, and when the concrete has hardened, the deck and the concrete together must support the entire load on the deck. A comparison of the typical profiles of composite and form decks is shown in Figure 18.27.

The anchorage of a floor deck to supporting joists or beams is similar to that of a roof deck, that is, through puddle welds. The connection of the longitudinal (side) edges of adjacent deck panels is also similar.

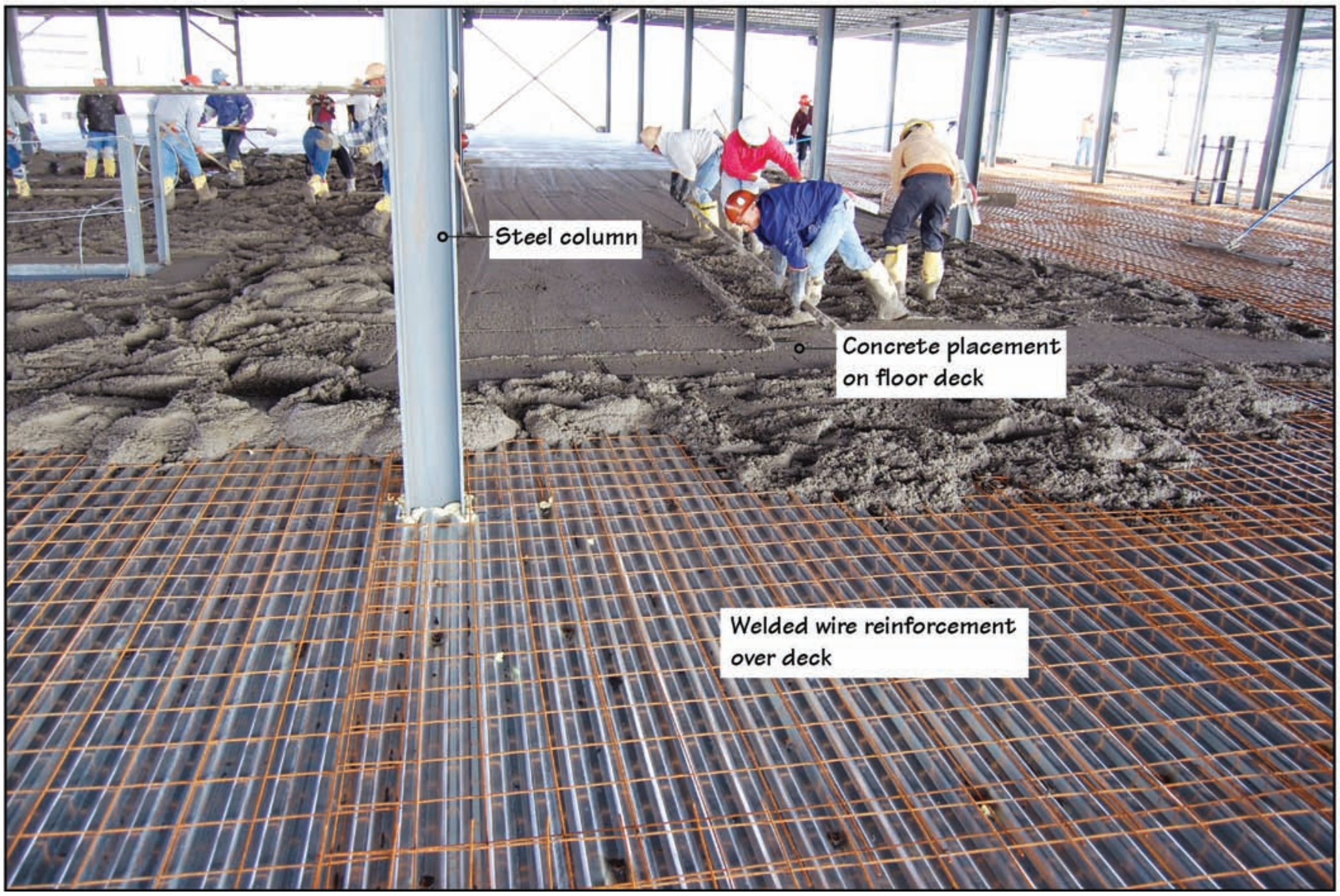
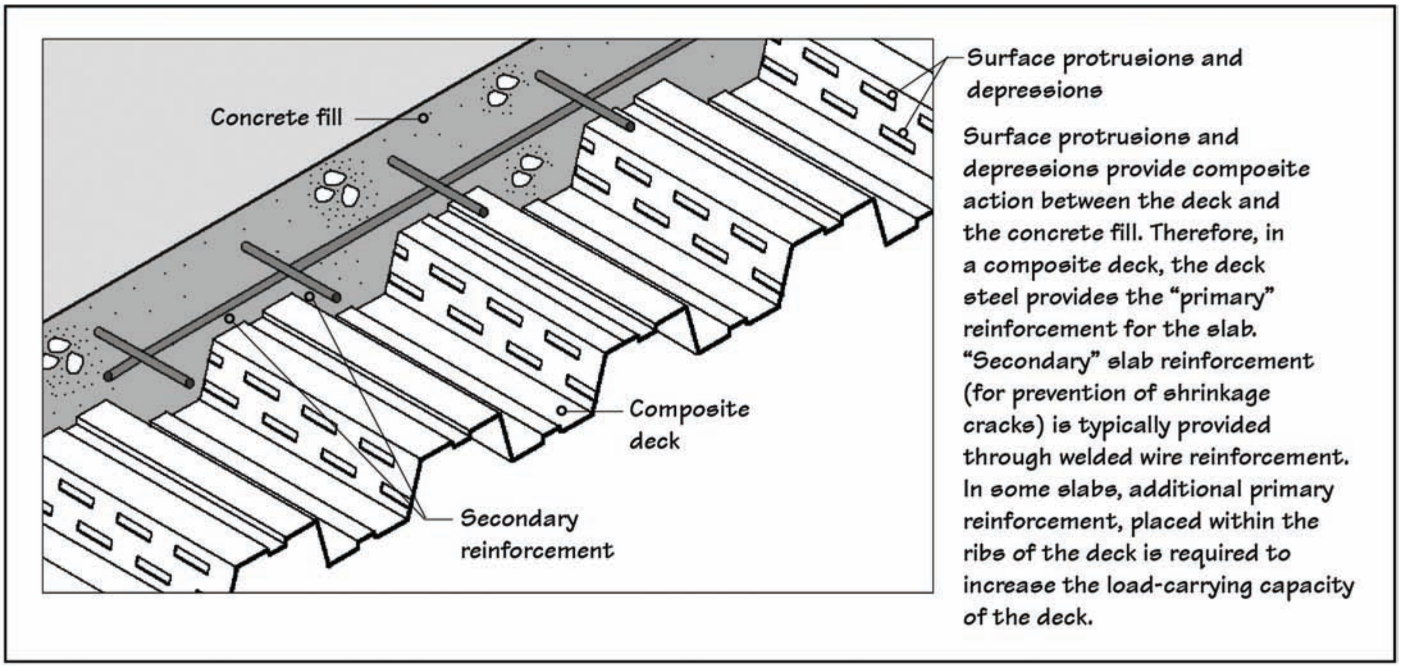
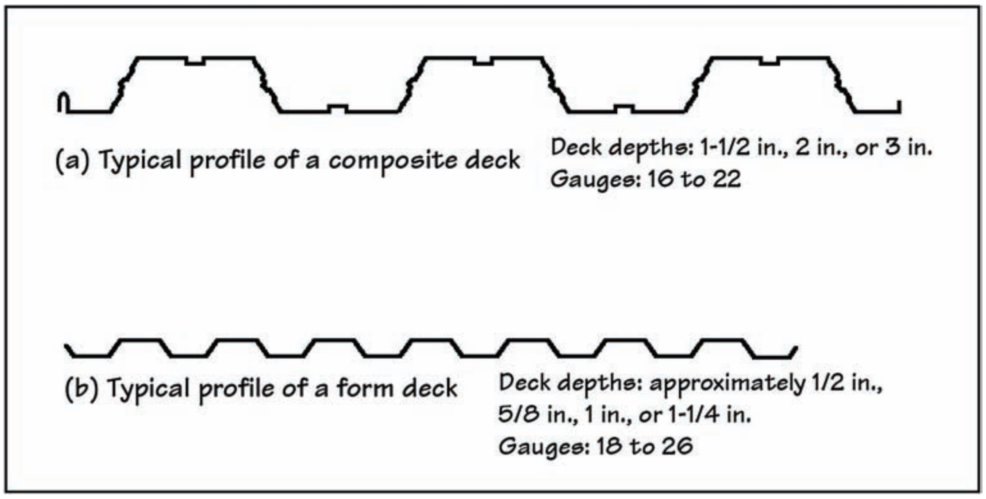

Steel column
Concrete placement on floor deck
Welded wire reinforcement over deck

FIGURE 18.25 This illustration shows the placement of concrete on a floor deck (a form deck in this case). Welded wire reinforcement (WWR) provides concrete reinforcing. (See Section 21.13 for the description of WWR.)



Surface protrusions and depressions provide composite action between the deck and the concrete fill. Therefore, in a composite deck, the deck steel provides the "primary" reinforcement for the slab. "Secondary" slab reinforcement (for prevention of shrinkage cracks) is typically provided through welded wire reinforcement. In some slabs, additional primary reinforcement, placed within the ribs of the deck is required to increase the load-carrying capacity of the deck.

FIGURE 18.26 A commonly used composite steel deck. (See Section 23.2 for the description of primary and secondary slab reinforcing.)



(a) Typical profile of a composite deck

Deck depths: 1-1/2 in., 2 in., or 3 in.
Gauges: 16 to 22

(b) Typical profile of a form deck

Deck depths: approximately 1/2 in., 5/8 in., 1 in., or 1-1/4 in.
Gauges: 18 to 26

FIGURE 18.27 Comparison between the general profiles, depths, and gauges of composite decks and form decks.

COMPOSITE ACTION BETWEEN FLOOR SLAB AND SUPPORTING MEMBERS

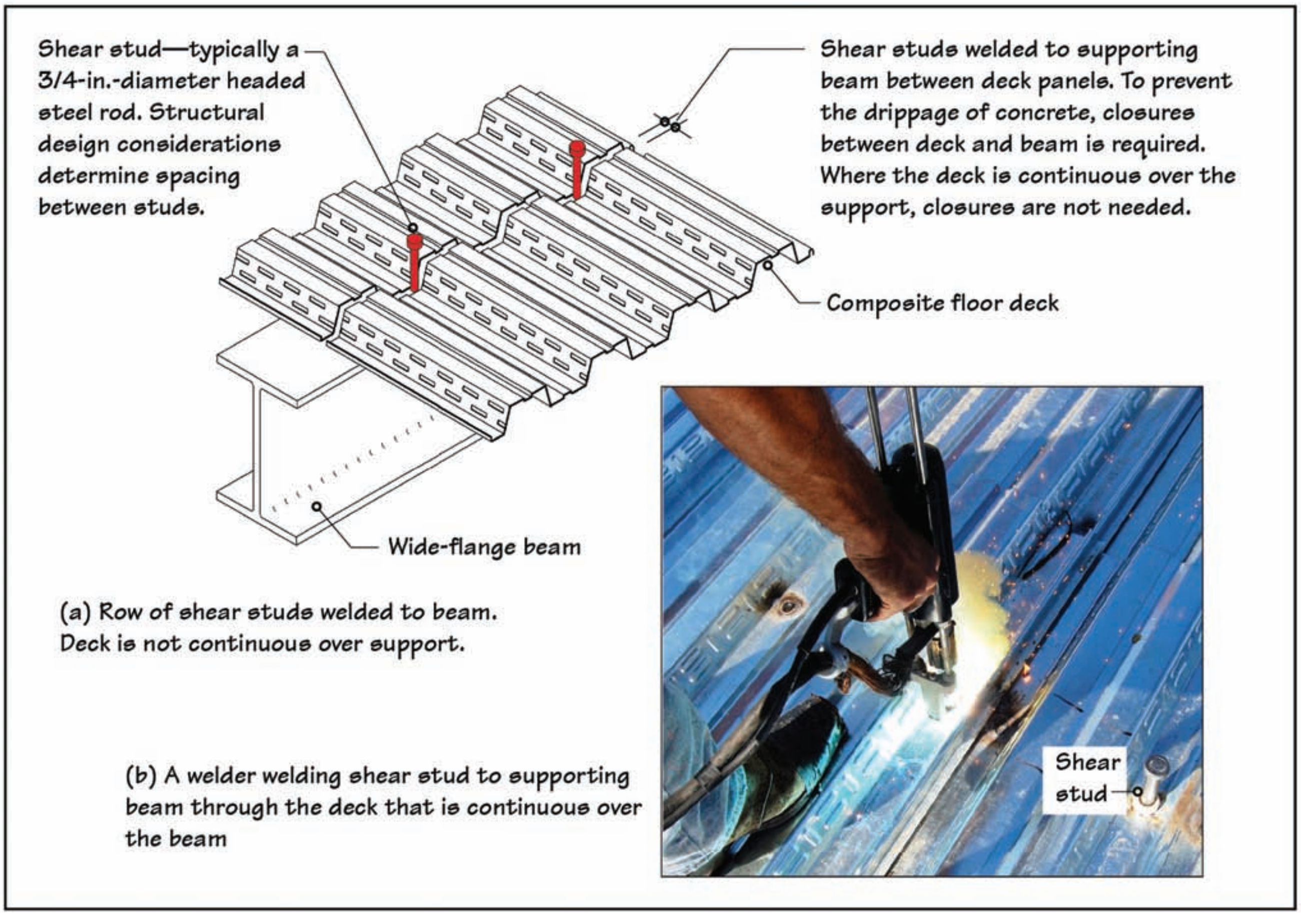
Both a composite deck and a form deck can be made to act compositely with the supporting beams by using shear studs, Figure 18.28. Shear studs prevent slippage of the deck under bending of the underlying beam. They are similar to nails that connect a plywood deck with supporting wood joists.

POUR STOPS AT SPANDREL BEAMS AND EDGES OF FLOOR OPENINGS

To terminate a concrete pour at the extreme edges of a floor deck, pour stops are used. A steel angle or a manufacturer-supplied standard pour stop is used for the purpose, Figure 18.29. If the pour stop is used for anchoring another building element, such as a glass curtain wall, the structural capacity of the pour stop should be examined.

18.7 CORROSION PROTECTION OF STEEL

Because steel (unlike aluminum) does not automatically form a protective oxide coating, it must be protected against corrosion. However, structural steel members enclosed by the building envelope do not require any protective coating unless they are in a corrosive environment.


Shear stud—typically a 3/4-in.-diameter headed steel rod. Structural design considerations determine spacing between studs.
Shear studs welded to supporting beam between deck panels. To prevent the drippage of concrete, closures between deck and beam is required. Where the deck is continuous over the support, closures are not needed.
Composite floor deck
Wide-flange beam
Shear stud

(a) Row of shear studs welded to beam. Deck is not continuous over support.

(b) A welder welding shear stud to supporting beam through the deck that is continuous over the beam

FIGURE 18.28 Use of shear studs for composite action between (concrete-topped) steel floor deck and beam.

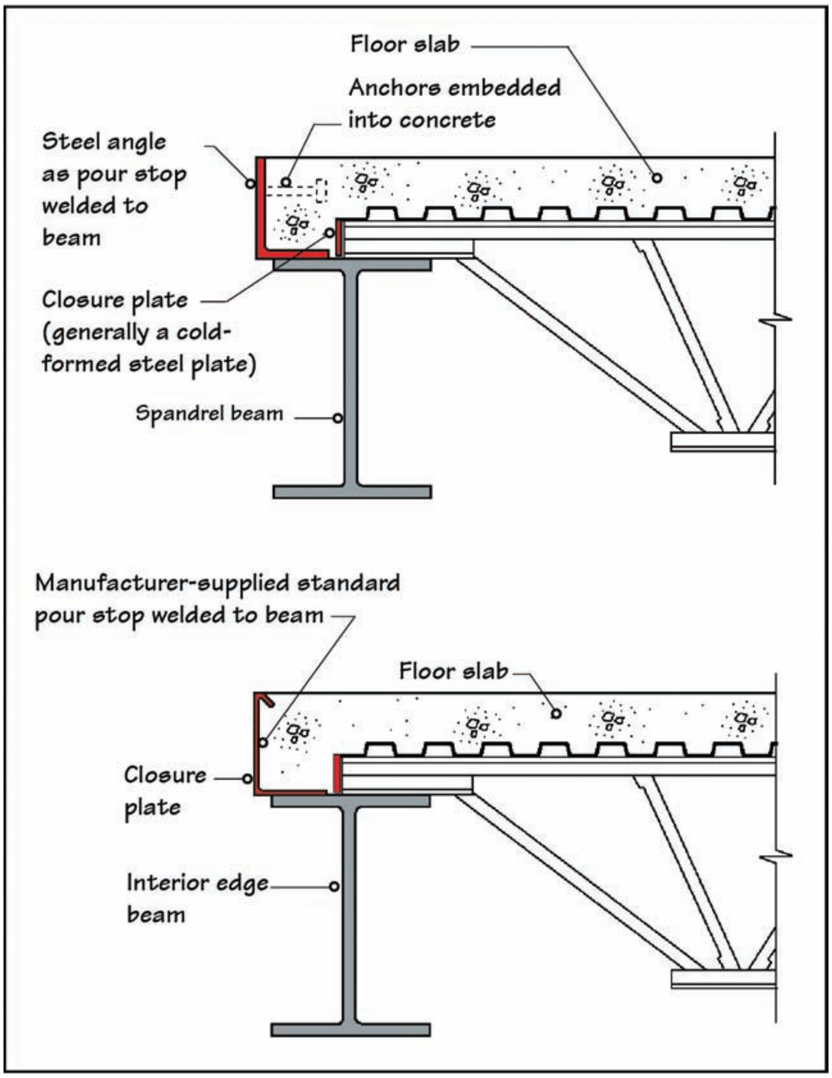

Floor slab
Anchors embedded into concrete
Steel angle as pour stop welded to beam
Closure plate (generally a cold-formed steel plate)
Spandrel beam
Manufacturer-supplied standard pour stop welded to beam
Floor slab
Closure plate
Interior edge beam

FIGURE 18.29 The use of pour stops at spandrel beams and interior mezzanine floor beams.

In other words, interior structural steel members can be left bare (mill-finished state) in most situations. This recommendation [Ref. 18.2] is based on the surface conditions disclosed by the demolition of several long-standing structures in which steel had no protective coating. These structures suffered no corrosion or the corrosion was localized to small areas that were affected by persistent water leakage or condensation.

Although bare steel is acceptable, almost all structural steel members generally receive a prime coat in the fabricator's shop before being delivered to the construction site. The prime coat provides temporary protection until the steel is wrapped by the building envelope. Structural steel that is permanently exposed to the atmosphere must, however, receive further protection. Additionally, concealed steel components that may be subjected to wetting, such as steel anchors buried in masonry or concrete, should also be protected.

Several protective coatings are available for steel to suit different environmental conditions, aesthetic requirements, and budgets. These include acrylics, epoxies, polyurethanes, and zinc coating. For exposed structural steel members, polyurethane coatings are the hardest, toughest, and most versatile. The prime coat is generally applied in the shop, followed by one or two field-applied finish coats. A well-applied polyurethane coating provides more than 20 years' protection.

For cold-formed and light structural steel members, zinc coating (referred to as *galvanizing*) is a cost-effective solution. Of the various types of galvanizing, hot-dip galvanizing is by far the most reliable and the most widely used.

HOT-DIP GALVANIZING

In the hot-dip galvanizing process, the steel member is immersed in a kettle of molten zinc, which is at a temperature of about 850°F (475°C). This results in the formation of a zinc-iron alloy coating that is metallurgically bonded to steel. After the member is removed from the kettle, the excess zinc is drained and shaken off. The galvanized member is then cooled in air or quenched in water. As a result of its immersion, the entire member is coated with zinc, including the protrusions, recesses, and corners.

Kettles up to 50 ft long are available. If a member is longer than 50 ft, it can be galvanized in two halves. After one half has been galvanized, it is removed; then the other half is immersed in the kettle.

Hot-dip galvanizing should be done after the member has been completely fabricated. No cutting, grinding, or process that eradicates the coating should be done after galvanizing.

The thickness of the coating influences the degree of protection. The thicker the coating, the greater the protection. The thickness of a zinc coating is specified as Gxx, where G stands for galvanizing and xx indicates the average coating mass in ounces per square foot (oz/ft^2) of the steel member. Thus, a G60 coating means that the member is coated on all of its surfaces with an average of $0.60\ oz/ft^2$ of zinc. If the member is a sheet, G60 means the presence of $0.30\ oz/ft^2$ of zinc on each surface of the sheet. A G90 coating indicates $0.90\ oz/ft^2$ of zinc coating on all surfaces.

In the SI system, the same zinc coating is specified as Zyy, where yy indicates the average coating mass in grams per square meter (g/m^2). Because $1\ oz/ft^2 = 305\ g/m^2$, a G60 coating is equal to Z180, and a G90 coating is equal to Z275.

Three levels of hot-dip galvanizing are commonly specified: G30 for a mildly corrosive environment, G60 for a more corrosive environment, and G90 or G120 for a highly corrosive environment.

NOTE

Corrosion—An Electrochemical Process

Corrosion is not simply a chemical process; it is an electrochemical process that results in the eating away of the surface of a metal when it is exposed to weather. It occurs when electrons flow through an electrolyte. (An electrolyte is a liquid that allows the flow of electrons through it.)

Water is a necessary ingredient for corrosion. Acidic water or water containing salt is a better electrolyte. That is why coastal regions are more corrosive than inland areas and deserts are less corrosive than humid regions.

EXPAND YOUR KNOWLEDGE

Corrosion of Metals

Metals, by virtue of their atomic structure, are chemically reactive materials. They react readily with atmospheric oxygen to form metal oxides, which are chemically stable. That is why metals are generally obtained on the earth's surface in the form of their oxides, that is, iron oxide (iron ore), aluminum oxide (bauxite ore), and so on.

Atmospheric Corrosion

Because of their reactivity, metals have a tendency to return to their original (oxide) state. The oxidation reaction obviously requires atmospheric oxygen, but it also requires the presence of water. The reaction is accelerated by the presence of atmospheric impurities because they, in combination with water, can form weak acids.

For example, sulfur released from automobile and industrial exhausts dissolves into rainwater and converts to weak sulfuric acid. Sulfuric acid exists in most contemporary urban environments. It was also present in the environment before the introduction of automobiles due to the burning of coal, which contains a substantial amount of sulfur.

EXPAND YOUR KNOWLEDGE

Water that contains salt also accelerates the oxidation of metals. Corrosion of metals is more rapid in coastal areas than in inland areas. Salt spread on roads in snow-prone regions accelerates the corrosion of steel bridges and of steel reinforcement embedded in floor slabs of parking garages. The oxidation of metals, referred to as *corrosion*, begins at the surface of the metal, and if the reaction is not interrupted, it proceeds inward and can corrode the entire metal over time.

The corrosion of steel results in the formation of iron oxide—a brown-colored material called *rust*. Because rust is a loose and flaky material, it separates from the steel member and exposes the member to further corrosion. The volume of rust is greater than that of the original iron. That is why the corrosion of reinforcing steel not only reduces the amount of steel, but also tends to spall the concrete.

By contrast with iron oxide, aluminum oxide, formed by the oxidation of aluminum, clings securely to aluminum. Being a stable compound, aluminum oxide forms a protective layer and prevents further oxidation of aluminum. When an aluminum surface is scratched and aluminum is exposed, a new oxide layer is immediately formed over the scratch, maintaining the protection.

Galvanic Corrosion

The type of corrosion just described is called *atmospheric corrosion* because it is caused by a metal's exposure to the atmosphere. An additional type of corrosion of interest to design and construction professionals is *galvanic corrosion*. Galvanic corrosion, also called *bimetallic corrosion*, is caused by the physical contact between two dissimilar metals. Galvanic corrosion is not chemically different from atmospheric corrosion; that is, both galvanic and atmospheric corrosion processes produce the same end product. The difference is that the contact between the two dissimilar metals changes the metals' respective corrosion rates. One metal corrodes more rapidly than its atmospheric corrosion rate, and the other metal corrodes more slowly. The change in their corrosion rates depends on the type of metals in contact.

The metal whose corrosion rate declines is called a *more noble* metal, and the one whose corrosion rate increases is called a *less noble* metal. The relative nobility of metals is given by the *galvanic series*, produced by Luigi Galvani in the late eighteenth century. The galvanic series for a few selected metals is given below. Of various metals, gold and platinum are the most noble, and magnesium and zinc are the least noble.

The change in the corrosion rates of metals that are close to each other in the galvanic series is smaller. The farther apart the metals are in the series, the greater the change in their respective corrosion rates. Thus, if zinc and copper, which are far apart in the series, are placed in contact, the corrosion rate of zinc will be accelerated and that of copper will decline substantially.

Galvanic corrosion is easily controlled by separating the metals from each other either by a plastic separator or by coating one or both metals. Coatings also inhibit atmospheric corrosion.

Galvanic Series of Selected Metals

Less	Magnesium
noble	Aluminum
	Zinc
	Steel
	Stainless steel
	Tin
	Lead
	Copper
	Bronze
	Brass
	Titanium
	Silver
More	Platinum
noble	Gold

18.8 FIRE PROTECTION OF STEEL

The fire endurance of steel is poor, and its inherent incombustibility gives a false sense of security. Exposed (unprotected) steel, unless it is very thick, cannot withstand long exposure to fire. Steel's yield strength and modulus of elasticity drop to nearly 60% of their original values at about 1,100°F (600°C)—a temperature that is well below the temperature used in a standard fire test.

Steel has a high coefficient of thermal expansion. When subjected to fire, an unrestrained steel member expands, pushing on the members to which it is connected. A restrained member develops high internal stresses. In either case, the consequences can be disastrous. It is important, therefore, that structural steel be protected against fire. Unprotected steel buildings may be used, but building codes severely limit the allowable areas and heights of such structures.

FUNDAMENTALS OF FIRE PROTECTION OF STEEL

There are basically two ways to protect steel against fire:

- Insulate the steel component with a noncombustible thermal insulation. Spray-applied fire protection and intumescent paints fall in this category.
- Encase the steel component with a noncombustible material with high thermal capacity, such as concrete, gypsum board, or water (see Section 5.8). These materials retard the buildup of temperature, producing the same end result as thermal insulation.

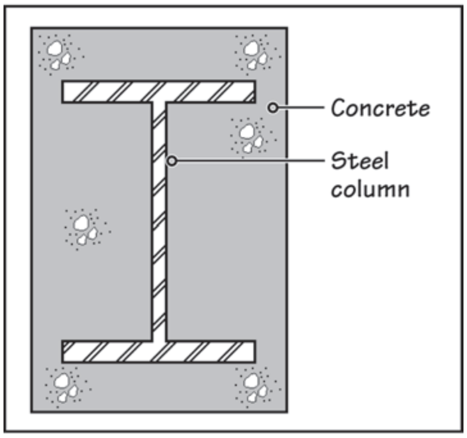


FIGURE 18.30 Encasing a steel member in concrete (or masonry) is one of the oldest methods of protecting steel against fire. The use of this method is relatively uncommon in contemporary construction because of the availability of more efficient and economical alternatives.

ENCASEMENT OF STEEL IN CONCRETE

Figure 18.30 shows a steel member encased in concrete. Concrete encasement is generally used in columns and floor systems that consist of reinforced concrete slabs supported by steel beams so that the concrete-encased steel beams function monolithically with the slab. The disadvantages of protecting steel with concrete encasement are the high cost of formwork and the large dead load it poses on the structure. It has, therefore, been replaced by more efficient techniques, which are lightweight and more economical, such as spray-applied fire protection and gypsum board encasement.

GYPSUM BOARD ENCASEMENT

Figure 18.31 shows steel members wrapped with gypsum board, in which gypsum boards are mechanically fastened to steel sections, usually screw attached to light-gauge steel studs, Figure 18.31. Almost any degree of fire rating can be obtained by varying the number of board layers. (See Chapter 16 for a discussion of gypsum boards.)

SPRAY-APPLIED FIRE PROTECTION

Spray-applied fire protection is by far the most commonly used method because of its lower cost and greater convenience. It has two disadvantages: (a) the finished profile of the steel component on which it is sprayed becomes jagged and uneven, and (b) sprayed material may come loose from the member with a decrease of adhesion over time. Two types of materials are used for spray-applied (or spray-on) protection:

- Mineral fiber and binder, usually fiberglass and Portland cement
- Cementitious mixture consisting of Portland cement mixed with a lightweight aggregate such as expanded perlite or vermiculite

NOTE

Use of Unprotected Structural Steel Framing Members

Unprotected steel in structural framing of building is routinely used. Unprotected steel-framed buildings, defined as Type II(B) construction(Chapter 7), are allowed by building codes for all occupancy groups except I-2 occupancy group (hospitals, nursing homes, etc.).

However, if protected steel framing is used for the same building, the built-up area allowed by the building codes is greater, depending on the type of construction used. Protected steel construction types may be Type I(A), Type I(B), or Type II(A). The allowable built-up area may also be increased through the use of automatic sprinklers (see Principles in Practice in Chapter 2).

Figure 18.32 shows spray-applied fire protection on a steel roof assembly. Note that the fire protection extends over steel joists as well as the roof deck. Figure 18.33 shows fire protection on a steel floor assembly. Note that the deck is not covered with protection because of the presence of concrete fill over the deck, which provides sufficient thermal capacity to obviate the need for insulation through spray-on protection. Floor decks may need spray-on protection if the required fire rating is high. Roof decks almost always require spray-on protection due to the absence of concrete fill on roof decks.

Virtually any amount of fire resistance can be obtained by varying the thickness of spray-on protection. For a given fire rating, the thickness of spray-on protection depends on the spray-on material and the thickness of the steel. The heavier the member, the thinner the required protection. However, a $\frac{5}{8}$-in. thickness per 1 h of fire

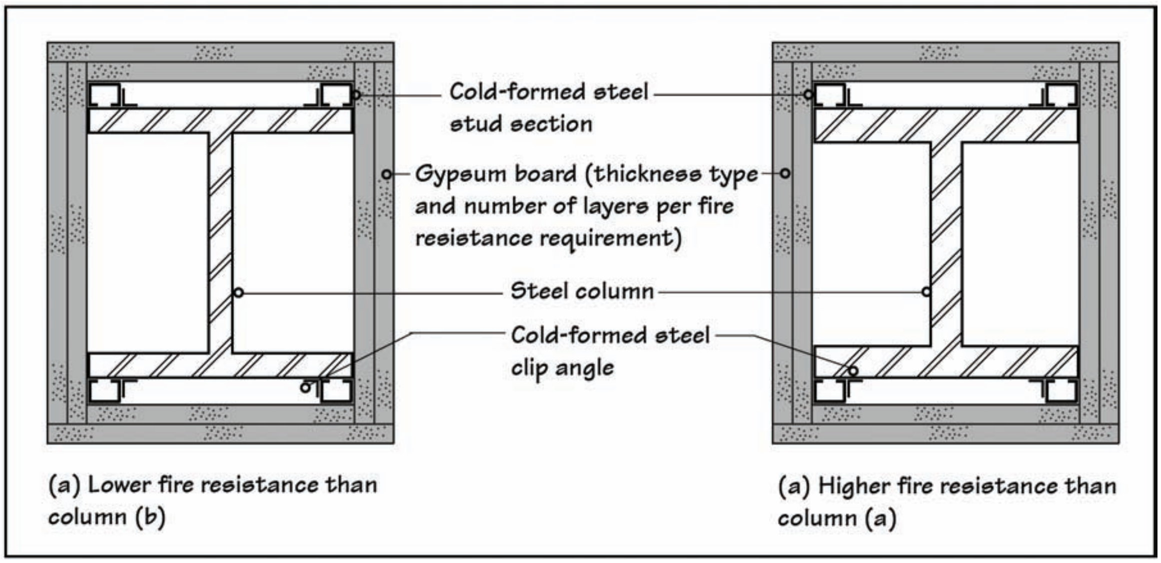

Cold-formed steel stud section
Gypsum board (thickness type and number of layers per fire resistance requirement)
Steel column
Cold-formed steel clip angle
(a) Lower fire resistance than column (b)
(a) Higher fire resistance than column (a)

FIGURE 18.31 Details of a steel column covered with gypsum board layers. Details **(a)** and **(b)** are identical except that the column in detail **(b)** is heavier than that of the column in detail **(a).** Because the thickness of steel also affects the member's fire resistance, in addition to the thickness and type of gypsum board, the fire resistance rating of column **(b)** is higher than that of column **(a).**

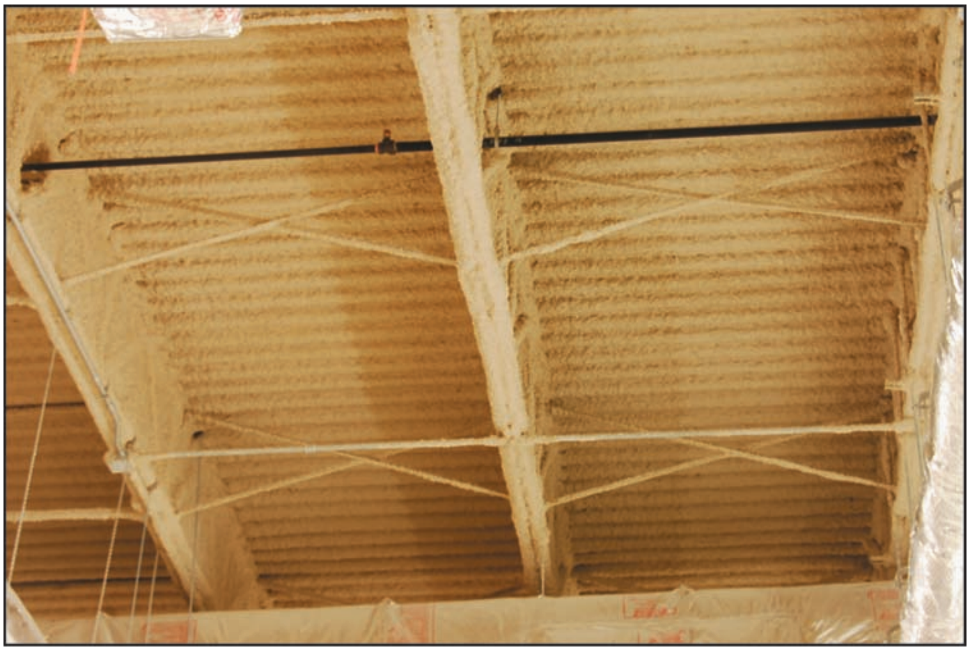


FIGURE 18.32 Spray-on fire protection of a steel roof assembly. Observe that both joists as well as the roof deck are protected.

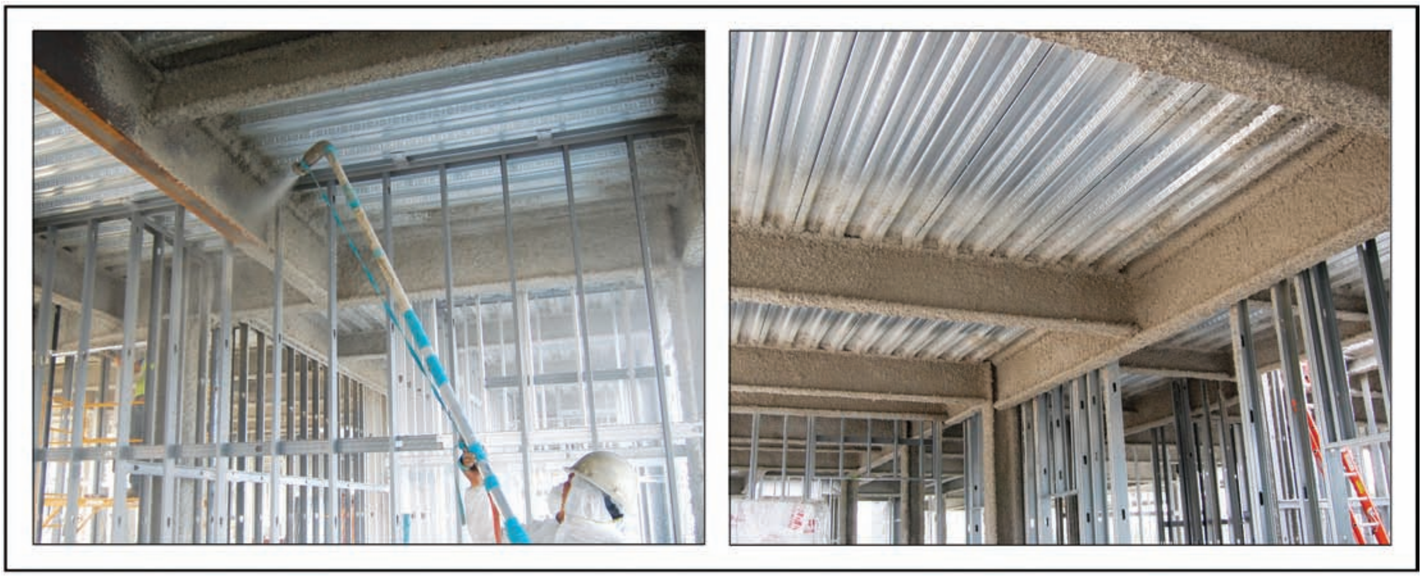


FIGURE 18.33 Spray-on fire protection on a steel floor assembly. Observe that the floor beams are protected. Fire protection is generally not necessary for the floor deck because of the concrete topping.

rating is a good rough estimate of the required thickness of protection. Thus, a 1-h rating is obtained by applying about $\frac{5}{8}$-in.-thick material, a 2-h rating by applying $1\frac{1}{4}$-in.-thick material, and so on.

The fire rating is not the only criterion that spray-on protection must meet. It must also meet the minimum requirements for damageability resistance, adhesion to steel, deflection (so that the protection does not delaminate when the steel member deflects under loads), air-erosion resistance, and corrosion resistance (spray-on protection also protects steel from corrosion).

INTUMESCENT PAINTS

An alternative to gypsum board encasement is intumescent paint on steel members. Intumescent paint is typically 20 mil to 50 mil (0.5 to 1.3 mm) thick. When exposed to the heat of fire, the paint intumesces, or swells, yielding an insulating char cover on steel that is 2 in. to 4 in. thick. It is this char layer that protects steel from fire. However, the char layer is damaged by long-term exposure to fire; hence, this technique can be used only for low levels of fire rating, generally not exceeding 2 h.

Intumescent paint is a thin film that does not alter the overall profile of steel sections. It gives the structure the look of exposed steel and is commonly used in situations where the expression of exposed steel is required from an architectural and interior design perspective.

Intumescent paints are available in different colors. Thus, the painted structure can be color coordinated with the overall character of the interior. Other advantages of intumescent paint protection are its abrasion resistance and its relatively smooth surface (which does not easily collect dust). It is, therefore, ideal for areas where a dust-free environment is required, such as laboratories and hospitals. If a washable top coat is provided on intumescent paint, the structure can be washed with water, which is an advantage in food-processing plants.

Intumescent paint protection, however, is far costlier than conventional spray-on fireproofing. It is, therefore, not practical for buildings where economy is a major consideration. In buildings with large areas of steel deck supported on steel beams and columns, intumescent paint may be used for beams and columns, but the deck may be protected by a more economical alternative.

SUSPENDED CEILINGS

Suspended ceilings consisting of gypsum lath and plaster, gypsum boards, or acoustical tiles are also used to provide fire protection to otherwise unprotected steel beams or trusses in roof-ceiling or floor-ceiling assemblies. The ceiling grid may be directly attached to, or hung from, the bottom flanges of beams or the bottom chords of trusses.

The effectiveness of such a system depends on how well the ceiling continues to perform as a barrier. Often the maintenance is not adequate, resulting in a defective ceiling tile or gypsum board not being replaced properly, so that hot gases enter the plenum space to attack the unprotected steel.

FOCUS ON SUSTAINABILITY

Sustainability Features of Steel

Steel can be easily recycled by melting old steel and reforming it, as discussed in Section 18.1. Large quantities of new steel are being made from steel recovered from old cars, washing machines, refrigerators, structural members from old buildings, and so on. The steel industry claims that along with aluminum, steel is the most recycled building material. In 2008, approximately 83% of steel was recycled.* In the United States, all structural steel sections, such as the W-shape, C-shape, and L-shape, are produced by the electric arc furnace process, which utilizes mostly recycled steel.

As mentioned earlier, steel does not corrode if used in interior locations. It is, therefore, a durable material even without any corrosion protection. Another sustainable feature of steel is that it lends itself readily to deconstruction, particularly if mechanical fasteners are used for component assembly. In a well-designed assembly, steel components can be disassembled, refabricated, and reassembled at a new location (and for a new use) without the need to recycle.

Steel structures, being lighter in weight than concrete and masonry structures, require smaller foundations, conserving the use of concrete and excavations.

Although the manufacture of steel produces pollution, there are no pollution issues with steel during its service. Unlike engineered wood components, there are no outgassing issues with steel. However, steel members protected by fibrous fire protection may dispel stray fibers in the air.

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* *Modern Steel Construction*, February 2010.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

19. Which of the following does not represent a steel joist series?
- **a.** H-series
- **b.** J-series
- **c.** K-series
- **d.** LH-series
- **e.** DLH-series

20. In the steel joist designation 24LH10, the number 24 gives the
- **a.** length of the joist in feet.
- **b.** depth of the joist in inches.
- **c.** weight of the joist in pounds per foot.
- **d.** number of web members.
- **e.** none of the above.

21. A K-series steel joist that is 20 in. deep cannot be used to span more than
- **a.** 20 ft.
- **b.** 25 ft.
- **c.** 30 ft.
- **d.** 35 ft.
- **e.** 40 ft.

22. Steel joists are braced against instability by
- **a.** horizontal bridging members at the bottom of the joists.
- **b.** horizontal bridging members at the top of the joists.
- **c.** (a) or (b).
- **d.** (a) and (b).
- **e.** none of the above.

23. Diagonal bridging may be used as an alternative to horizontal bridging to stabilize steel joists.
a. True **b.** False

24. Steel joists and joist girders are best utilized in a building that has concentrated loads.
a. True **b.** False

25. Steel roof decks are either form decks or composite decks.
a. True **b.** False

26. Steel floor decks are either form decks or composite decks.
a. True **b.** False

27. The thickness of sheet steel in a roof or floor deck is generally specified in terms of
- **a.** inches.
- **b.** millimeters.
- **c.** gauge number.
- **d.** any one of the above.

28. Which of the following decks requires structural concrete topping?
- **a.** Form deck
- **b.** Composite deck
- **c.** Floor deck
- **d.** All of the above
- **e.** None of the above

29. Roof decks are anchored to supporting members by continuous welds along the support lines.
a. True **b.** False

30. A pour stop is generally used with
- **a.** roof decks.
- **b.** floor decks.
- **c.** (a) and (b).
- **d.** none of the above.

31. Two dissimilar metals are generally separated from each other by a separator, which helps to prevent
- **a.** atmospheric corrosion.
- **b.** galvanic corrosion.

32. In a galvanized steel plate that carries the designation G60, the number 60 means that
- **a.** the total mass of zinc coating on both surfaces of the plate is 60 oz/ft^2.
- **b.** the total mass of zinc coating on each surface of the plate is 60 oz/ft^2.
- **c.** the total mass of zinc coating on both surfaces of the plate is 60 g/ft^2.
- **d.** the total mass of zinc coating on each surface of the plate is 60 g/ft^2.
- **e.** none of the above.

33. Spray-on fire protection materials for steel contain
- **a.** Portland cement with mineral fibers or lightweight aggregate.
- **b.** polymer-based cement with mineral fibers or lightweight aggregate.
- **c.** Portland cement with normal-weight aggregate.
- **d.** polymer-based cement with normal-weight aggregate.
- **e.** any one of the above, depending on the manufacturer.

34. Spray-on fire protection of steel gives a much cleaner appearance than gypsum board encasement of steel.
a. True **b.** False

35. Fire-protection of structural steel framing members is mandated by building codes for all buildings.
a. True **b.** False

REVIEW QUESTIONS

1. Discuss the basic differences (in terms of chemical composition and important properties) among wrought iron, cast iron, and steel. Where would you recommend the use of wrought iron?
2. Discuss the two methods used in manufacturing steel, giving their relative advantages and disadvantages.
3. Discuss the difference between hot rolling and cold forming of steel and their uses in making steel components.
4. Sketch the commonly used hot-rolled sections used in building construction.
5. Using sketches, show the important difference between the W-shapes used for beams and those used for columns.
6. Using sketches and notes, explain:
    - a. what a plate girder is and where it is used.
    - b. what a built-up steel section is and where it is used.
7. Sketch the elevation of a typical K-series joist.
8. Sketch the end of a K-series joist in three dimensions. What is the standard end-bearing depth of a K-series joist?
9. Using sketches and notes, explain how joists and joist girders are stabilized against overturning.
10. Discuss the two basic approaches used for fire protection of steel.
11. In using spray-on fire protection for floor and roof assemblies, we generally apply the protection on roof decks and supporting beams, but in the case of the floor decks, we generally apply it only on the supporting beams, leaving the floor deck without spray-on protection. Explain the reason.

CHAPTER 19

Structural Steel Construction

CHAPTER OUTLINE

19.1 Preliminary Layout of Framing Members

19.2 Bolts and Welds

19.3 Connections Between Framing Members

19.4 Steel Detailing and Fabrication

19.5 Steel Erection

PRINCIPLES IN PRACTICE: Fundamentals of Frame Construction

The previous chapter covered various aspects of steel as a construction material—for example, fundamentals of steel manufacturing, types of steel components, and the methods used for protecting steel from corrosion and fire. This chapter deals with the application of that information to the design and construction of steel-frame buildings. It begins with the basics of structural framing, that is, location, and spacing of the components of: (a) the building's vertical support subsystem (columns and [or] walls) and (b) the building's horizontal support subsystem (floors and roof).

The structural frame of a steel building is constructed by assembling prefabricated steel components at the site. This is in contrast to the buildings whose structural system consists of load-bearing masonry or cast-in-place reinforced concrete. In these buildings, almost the entire structure is site-constructed, with virtually no prefabrication. Therefore, issues related to component fabrication, component erection, and component assembly are important in a steel structure and are discussed in this chapter.

A unique feature of steel structures (as distinct from wood, cast-in-place concrete, and masonry structures) is that the assembly details—details of the connections between steel components—are not prepared by the architect or the structural engineer, but by the steel detailer. Steel detailing is, therefore, a specialized expertise. As explained in the chapter, steel detailing may be done either by an independent detailing company or by an in-house outfit of a steel fabricator.

19.1 PRELIMINARY LAYOUT OF FRAMING MEMBERS

Preparing the *preliminary framing layout* of a steel-frame building (and also of wood or concrete buildings) is not simply a structural engineering exercise. It involves careful integration of structural considerations with several nonstructural considerations, such as HVAC, the building envelope, fire resistance, interior finishes, aesthetics, and cost. Because of its integrative nature, preparation of the preliminary framing layout is at the heart of an architect's expertise and is generally undertaken during the design development phase (see Chapter 1).

For a small or midsized building, an experienced architect would generally prepare the layout without the consultants' help. For a complex or large building, coordinating this activity with the consultants is usually necessary. The final framing layout is generally prepared by the structural engineer.

FRAMING PLANS AND THE STRUCTURAL GRID

The framing layout of a structure is usually prepared in plan view; therefore, it is referred to as a *framing plan*. Generally, a roof framing plan is different from a floor framing plan because of the difference in floor and roof loads. In some cases, framing plans may also differ from floor to floor. For example, the ground floor of a building may have large areas requiring larger column spacing in comparison with that at the upper floors. This and other differences will require framing plans to differ from floor to floor.

In preparing the framing plans, establishing the *structural grid* is the first step. A majority of buildings are either rectangular in plan or rectangle-based, such as an L-shape, T-shape, and so on. For such buildings, the structural grid is orthogonal, that is, the grid consists of two sets of lines perpendicular to each other. Additionally, several buildings, though rectilinear in plan, have parts that break from rectangularity, such as triangles, trapeziums, and so on. For these buildings, the grid is partially orthogonal and partially nonorthogonal. Though uncommon, the grid in some buildings may be entirely nonorthogonal, such as a triangular grid.

A structural grid determines the column locations, which are generally placed at the intersection of the grid lines. Therefore, the grid lines are also called *column lines*. The grid also defines the orientation of the components constituting the floors and roof. As discussed in Chapter 18, a floor or roof in a steel-frame building consists of: (a) beams or beamlike members, such as girders, joist girders, and joists; and (b) floor and roof deck panels. In most buildings, the deck panels are the *tertiary components* of the floor or roof, while the beams or beamlike members form the *primary* and *secondary components*.

The primary components span along one direction of the grid and support the secondary components that span along the other grid direction. The secondary elements support the tertiary elements—the deck panels—which span perpendicular to the secondary elements. Thus, the load from a roof or floor is transferred from the deck panels to secondary components, and then to the primary components, and finally to the columns. Thus, an important feature of the framing of a floor or roof of a steel building is that all components are *one-way components*, that is, they span along one direction only. This is in contrast to cast-in-place concrete slabs, which may either be *one-way* or *two-way slabs*.

For the primary and secondary elements in most buildings, the choice is between the use of W-sections or steel joists, as indicated by the following four alternatives:

- W-sections for both primary and secondary elements are shown Figure 19.1. In this arrangement, the primary elements are generally called *girders* and the secondary

NOTE

Structural Grid and Structural Bays

The space enclosed by adjacent column lines is called a *structural bay* or simply a *bay*. In a building, the number of bays in one direction may be different from those in the other direction. Thus, in Figure 19.5, the number of bays in the horizontal direction is four and the number of bays in the vertical direction is three.

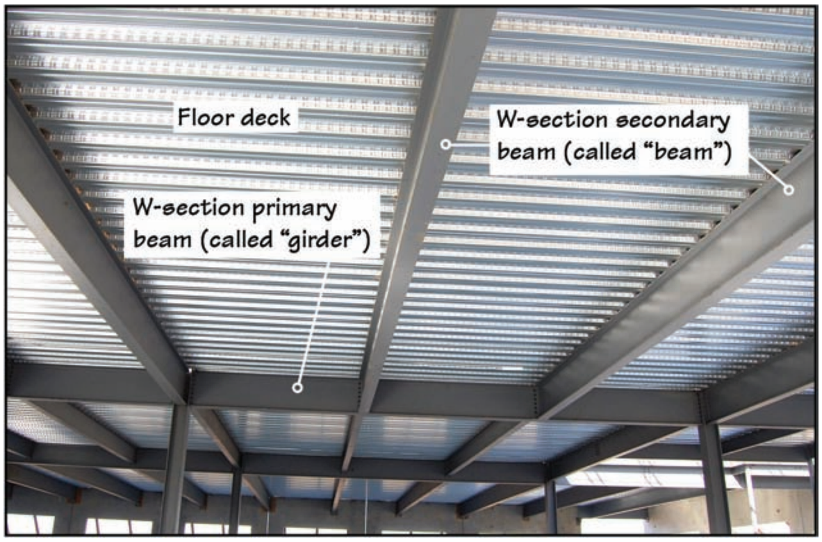

Floor deck
W-section secondary beam (called "beam")
W-section primary beam (called "girder")

FIGURE 19.1 A floor structure with W-sections for primary and secondary framing elements. Note the hierarchy in load transfer mechanism.

The floor load is transferred from the deck panels (tertiary elements) to secondary elements (secondary beams). From the secondary beams, the load is transferred to the primary elements (primary beams), and then to columns.

Instead of using the terms, "primary beam" and "secondary beam", the terms "girder" and "beam", respectively, are more common. The term "girder" is used for a beam that supports other beams.

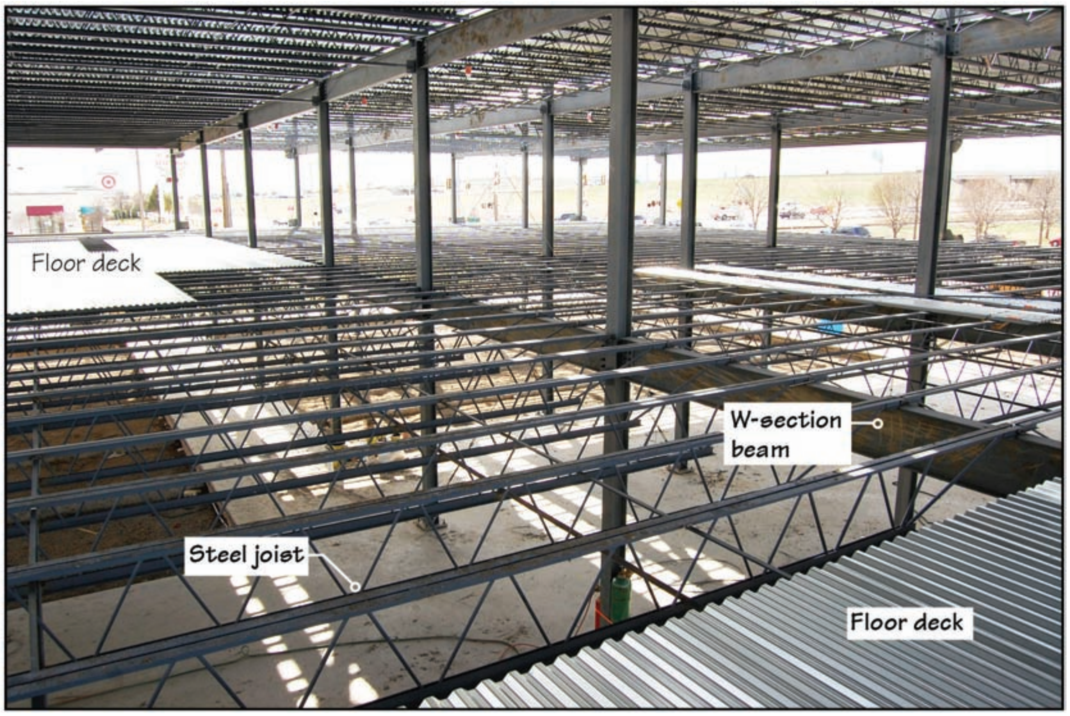


FIGURE 19.2 A floor structure with W-sections as primary framing elements and steel joists as secondary elements. Note the hierarchy in load transfer mechanism. The floor load is transferred from tertiary elements (deck panels) to joists, from joists to W-section beams, and then to columns. The photograph was taken during the installation of floor deck on the second floor of the building, making the ground-floor structure visible through second-floor framing elements.

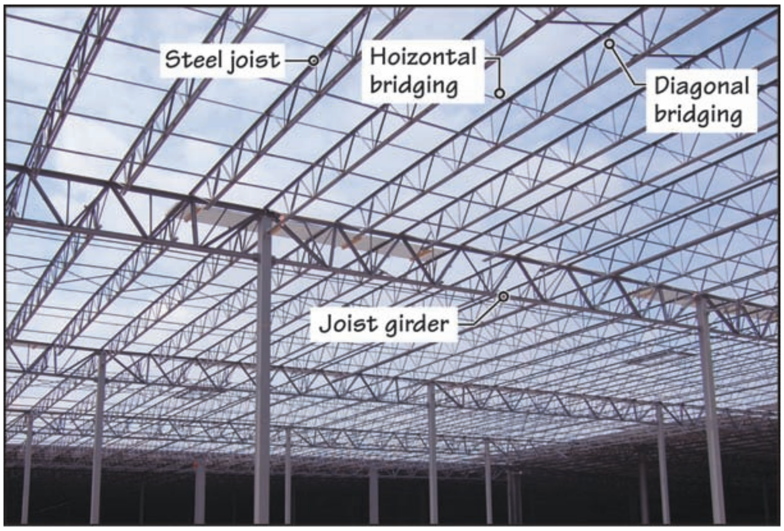


FIGURE 19.3 A roof structure with steel joist girders as primary framing elements and steel joists as secondary elements. Note that the roof load is transferred from deck panels to joists, from the joists to joist girders, and then to columns.

See Figure 18.22 for an explanation of horizontal bridging elements. Diagonal bridging is generally required at the center of joists.

elements are called *beams*. Some designers may refer to the primary elements as *beams* and the secondary elements as *intermediate beams*.

- W-sections for primary elements and steel joists for secondary elements are shown in Figure 19.2.
- Steel joist girders or trusses for primary elements and steel joists for secondary elements are shown in Figure 19.3.
- In some buildings, such as those with load-bearing walls, the secondary supporting elements may be omitted and the roof deck may be supported directly on the primary elements, Figure 19.4.

LATERAL LOAD RESISTANCE

The structural framing of a building must consider both gravity and lateral loads. Therefore, simultaneously with the preparation of the floor and roof framing plans, the architect (in consultation with the structural engineer) should determine how to provide lateral load resistance to the structure. In a steel-frame building, the choice is between the use of the following alternatives or their combinations:

- Rigid frames
- Braced frame

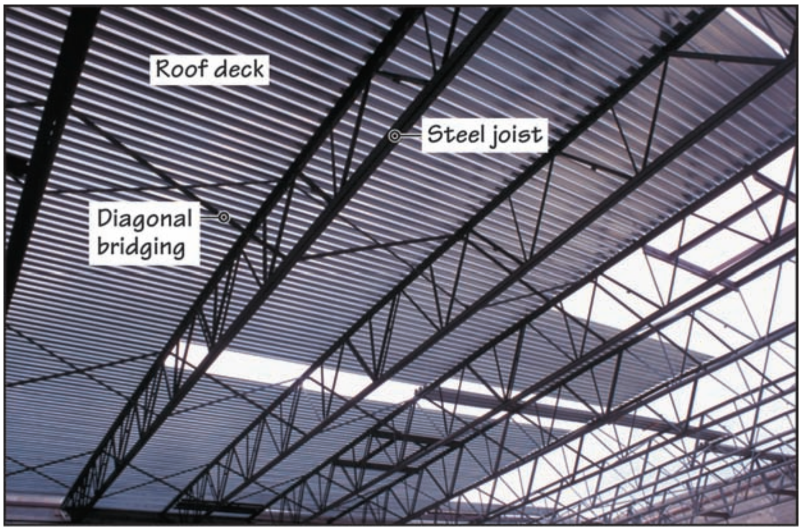


FIGURE 19.4 In this roof structure, the roof deck panels transfer the load to steel joists, which transfer the load to a masonry wall. Thus, the joists function as primary elements and the deck panels as secondary elements. Observe the daylight filtering through the deck. This is because the deck is a perforated (acoustical) deck; see Figure 18.25(g).

- Reinforced concrete shear walls
- Steel shear walls

The concepts related to these alternatives are explained in detail in the Principles in Practice section at the end of this chapter. Reading (even browsing) through this section at this stage should be helpful to the reader. The concept of framing is presented in the following examples.

Examples of Framing Layouts

A typical floor-framing plan of a low-rise rigid-frame rectangular building, using W-sections for both girders and intermediate beams, is shown in Figure 19.5. A version of the same framing plan using steel joists as secondary elements is shown in Figure 19.6. Figure 19.7 shows the framing plan of the same building using braced frames instead of rigid frames.

The preliminary depth of floor- and roof-framing members should be established at this stage, in addition to the type of floor and roof decks to be used. This information helps to provide the approximate floor-to-floor height of the building. The exact dimensions of the framing elements are established after the detailed structural design of the building has been completed by the structural engineer.

19.2 BOLTS AND WELDS

Connections between structural steel members can either be bolted or welded. Riveting, which was used extensively at one time, is no longer used.

Bolts

Steel bolts are of two types:

- *Unfinished* (or *common* or *ordinary*) *bolts* are made from carbon steel and generally have the same stress-strain characteristics as A36 steel. As per ASTM specifications, they are classified as A307 bolts. The use of A307 bolts has decreased significantly since the introduction of high-strength bolts.
- *High-strength bolts* are based on ASTM specification A325 or A490. A325 bolts are made from heat-treated carbon steel and have an approximate yield stress of 85 ksi. A490 bolts are made from a heat-treated steel alloy and have a yield strength of 120 ksi. A325 bolts are more commonly used because they cost less.

Snug-Tight Connection

For most structural steel connections, bolts are tightened to what is called a *snug-tight condition*. This condition is obtained when the connected members have been bolted together using a spud wrench with the full force of a person, Figure 19.8. The load transfer between members in a snug-tight connection (also called a *bearing connection*) occurs through shear in the bolts.

NOTE

Spacing of Framing Members

The spacing of columns is generally a function of the architectural plan. If the dimensions of bays are unequal, the primary horizontal framing members should generally be placed along the shorter dimension, and the secondary members should be placed along the longer dimension (Figure 19.5). This strategy reduces the difference between the depths of members and also yields an economical framing system.

If the secondary members are W-shape beams, typical spacing between them is 8 ft to 12 ft. If joists are used as secondary members, their typical spacing is 2 ft to 4 ft for floors and 4 ft to 6 ft for roofs.

Approximate Depths of Horizontal Framing Members

Depth of joist = span/20; depth of joist girder = span/14

Depth of W-section beam = span/22

Depth of W-section girder = span/16

See also Appendix B.

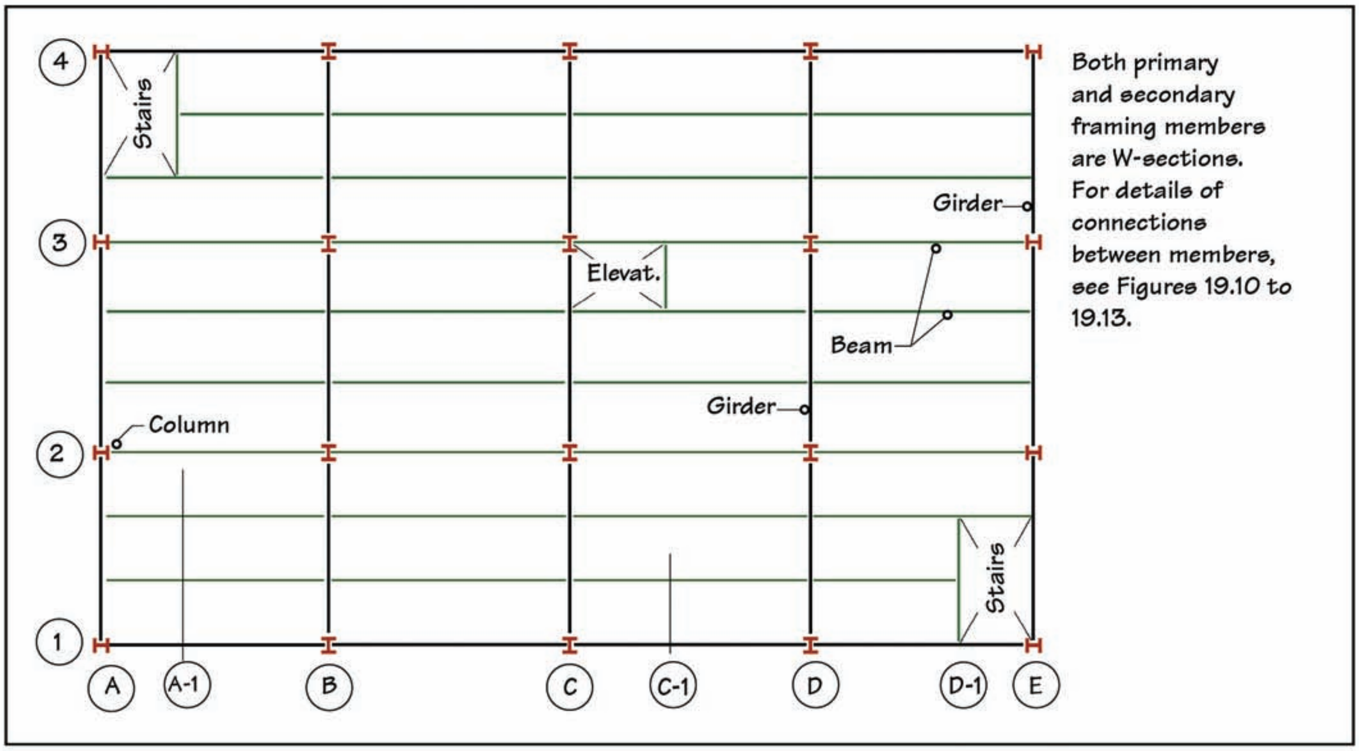

4
3
2
1
A
A-1
B
C
C-1
D
D-1
E
Stairs
Elevat.
Stairs
Girder
Girder
Beam
Column
Both primary and secondary framing members are W-sections. For details of connections between members, see Figures 19.10 to 19.13.

FIGURE 19.5 A typical floor framing plan for a steel rigid-frame building using W-sections for primary and secondary framing members. Observe that column grid lines are identified by A, B, C, and so on along one direction and 1, 2, 3, and so on along the other direction.

Rigid frames have been identified by black lines. Because rigid frames provide lateral stability (resistance to lateral loads), they need to be provided in both major directions of the building. Thus, in this building, (three-bay) rigid frames have been provided along grid lines A, B, C, D, and E, and (four-bay) rigid frames along grid lines 1 and 4.

A rigid frame means that the connections between the beams and columns are rigid connections. Thus, in this building, the connections between beams and columns along grid lines A, B, C, D, E, 1, and 4 are rigid connections. All other beam-column or beam-beam connections are simple (shear) connections.

In a rigid-frame building (such as this one), every column line does not need to be a rigid frame. The number of rigid-frame lines along a given direction depends on the magnitude of lateral load on that facade—a function of building length and lateral load intensity. Thus, because this building is longer along grid lines A, B, C, and so on, every column line is a rigid-frame line. In the other direction, only two out of four column lines are rigid-frame lines because of the smaller length of the building in that direction. In a low-rise building, rigid frames along grid lines B, C, and D (or B and D) may be replaced by simple frames.

The columns along grid lines A and E have been turned through 90° to increase the stiffness of the frames along grid lines 1 to 4.

To fully appreciate the essence of framing layout of a building, the reader should read Principles in Practice at the end of this chapter.

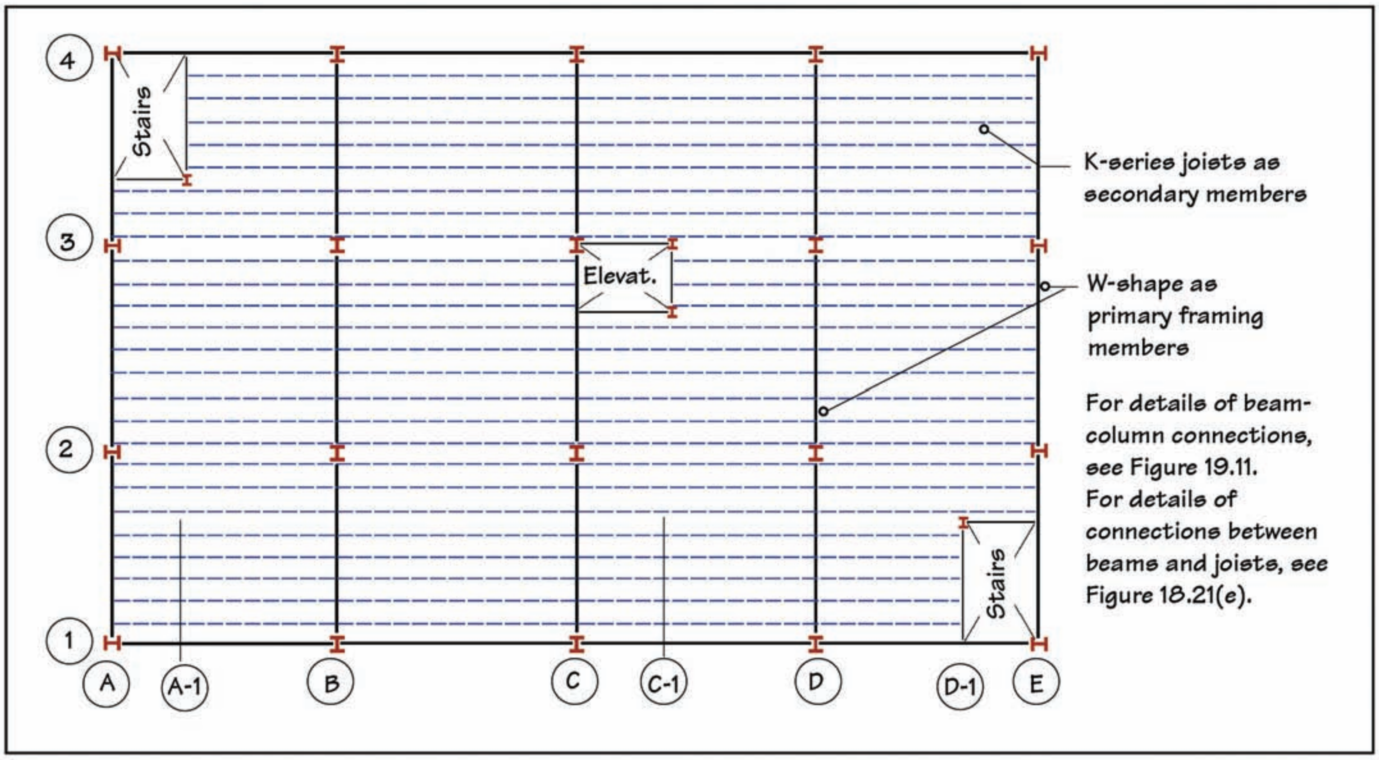

4
3
2
1
A
A-1
B
C
C-1
D
D-1
E
Stairs
Elevat.
Stairs
K-series joists as secondary members
W-shape as primary framing members
For details of beam-column connections, see Figure 19.11.
For details of connections between beams and joists, see Figure 18.21(e).

FIGURE 19.6 Floor framing plan of the rigid-frame building in Figure 19.5 with steel joists as secondary framing members instead of W-section beams. Rigid-frame lines are the same as in Figure 19.5, that is, along grid lines A, B, C, D, and E in one direction and along grid lines 1 and 4 in the other direction.

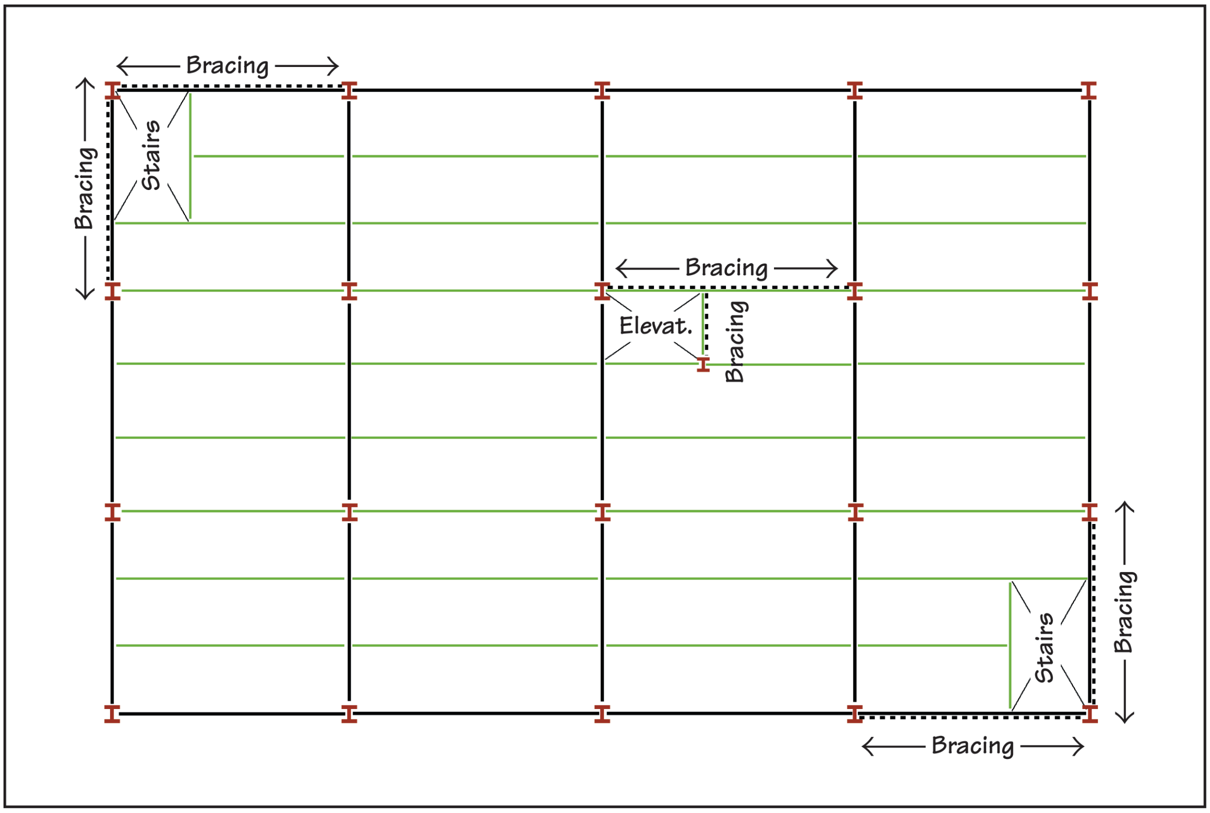


FIGURE 19.7 Framing plan of a typical braced-frame building. Braced frames have been identified by dashed lines. Because braced frames provide lateral stability (resistance to lateral loads), they need to be provided in both major directions of the building. Thus, in this building, there are four exterior braced bays and two interior braced bays. In many buildings, exterior braced bays are avoided; see Principles in Practice at the end of this chapter. All beam-column and beam-beam connections are simple connections.

SLIP-CRITICAL BOLTED CONNECTION

Another commonly used bolted connection is a *slip-critical connection*. The bolts in a slip-critical connection are tightened to a (high) tensile stress so that shear resistance is provided through friction between the connected surfaces, not through bearing, as in a snug-tight connection. In a slip-critical connection, the bolts are first brought to a snug-tight condition. Subsequently, they are tightened further until the bolt shank is under a predetermined level of tensile stress.

There are four ways of tightening a bolt to obtain a predetermined level of tensile stress. The oldest method is the *turn-of-nut method*. In this method, the bolt shank and nut are marked after the joint has been snugged. Then a specific amount of rotation is induced in the nut with respect to the bolt, generally from a one-third to a full turn beyond the snug-tight condition.

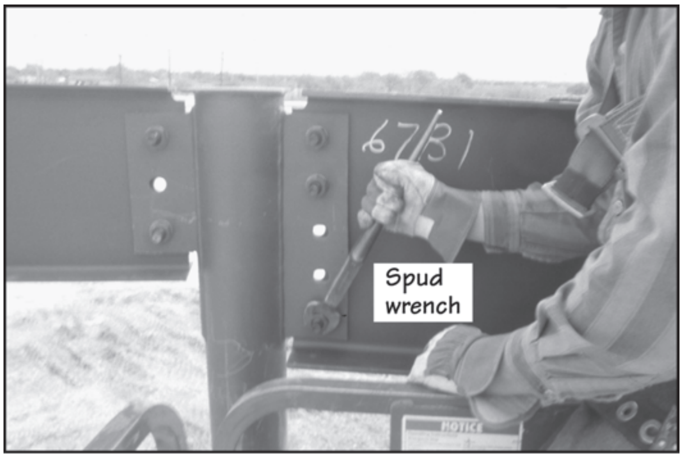
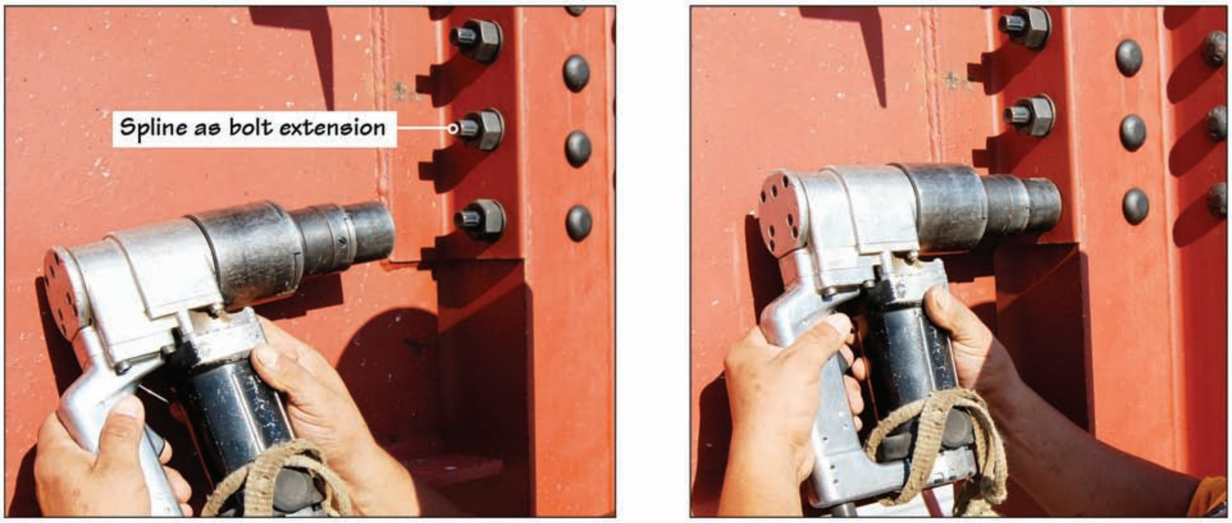


FIGURE 19.8 A typical spud wrench for making snug-tight bolted connections.

The success of the turn-of-nut method depends on the correct snugging of the joint and also on ensuring that the bolt head will not turn on further tightening. Two persons are, therefore, required to execute the tightening. One person prevents the bolt from turning, and the other person turns the nut with the help of a wrench. The turn-of-nut method cannot be used if the members are painted with a compressible paint.

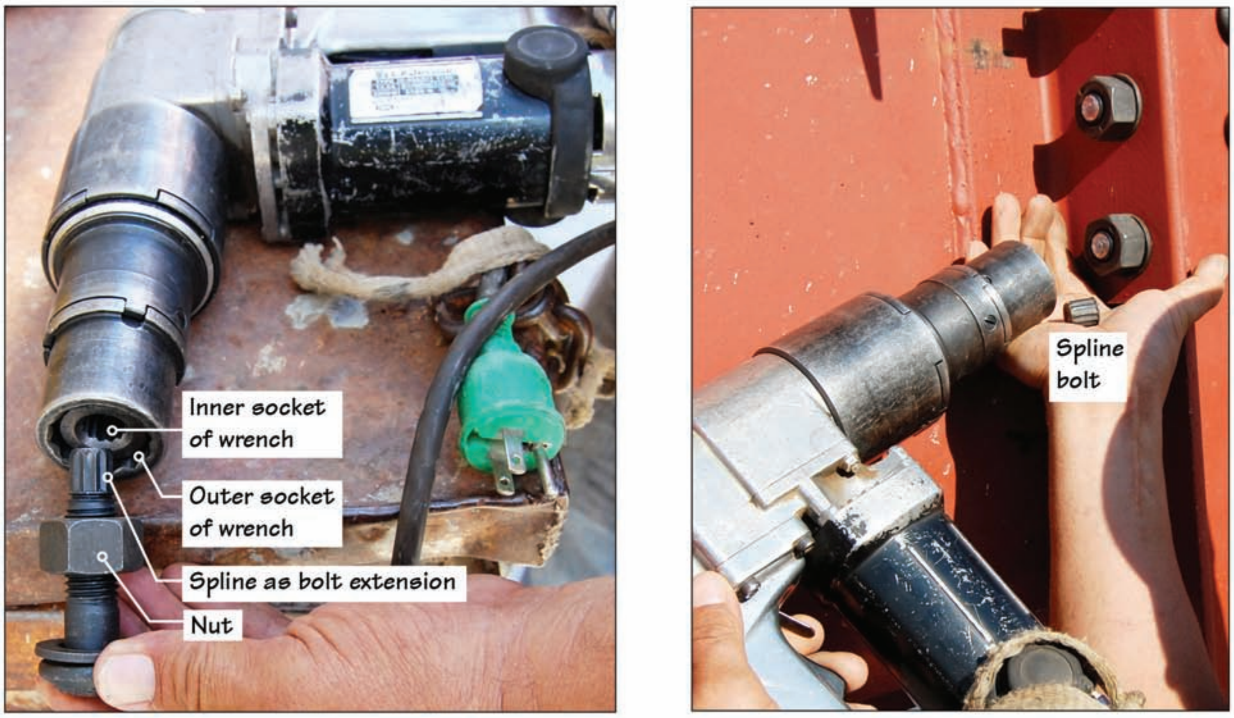
A more commonly used method is the *twist-off bolt method*. In this method, a special electric wrench is used that induces a predetermined torque in the bolt. The torque induces the required tension, after which the splined bolt extension twists off the bolt, Figure 19.9. This connection can be made by only one person.

Two other methods of obtaining slip-critical connections are the *calibrated wrench* and *direct-tension indicator* (DTI) methods. Slip-critical connections are generally required where the members are subjected to excessive vibration and/or fatigue and where oversized holes are used for easier fit. They are more expensive than bearing-type connections. However, when made through the twist-off method, they make connection inspection and quality control considerably easier.



(a) The nut-and-bolt connection is brought to a snug tight condition using a spud wrench before using the tension control wrench.

(b) When the tension control wrench is placed over the connection, the inner socket of wrench engages the spline and its outer socket engages the nut, as shown in (c).



(c) A close-up of the mouth of tension control wrench showing its inner socket that engages with the spline and the outer socket that engages with the nut.

(d) When the predetermined torque is reached after starting the wrench, the spline bolt extension twists off for disposal.

FIGURE 19.9 Steps in making a slip-critical connection through twist-off bolt method.

WELDS

Welding is a process by which connected steel parts are brought to a plastic or fluid state through heating of the parts, allowing them to fuse together, generally with the addition of another molten metal. Welding may be done using either gas welding or arc welding. In arc welding, used more commonly today, two terminals of a high-voltage electric circuit are brought close together, creating a sustained spark across the space between the terminals. A temperature of 6,000°F to 10,000°F (3,300 to 5,500°C) is produced in the arc.

One of the terminals in arc welding is the electrode, which is in the welder's hand, and the other terminal is provided by the two metals to be welded together. In the welding process, the electrode also melts and becomes part of the connection between the two metals being fused.

Welding versus Bolting

Welding has a much larger range of applicability than bolting. For example, hollow structural steel sections (round or rectangular) cannot be easily bolted together, but they can be easily welded.

Welded connections also eliminate the need for bolts and connection gusset plates, which can amount to a substantial saving of steel in some structures. Welding also creates continuity between the connected members, which is more difficult to obtain through bolting. However, welding requires a much greater level of skill than bolting. Welding should preferably be carried out under the controlled conditions of a shop. Good welding practice requires that the members to be welded must be dry and free from dirt and grease. Therefore, field welding is generally avoided as much as possible.

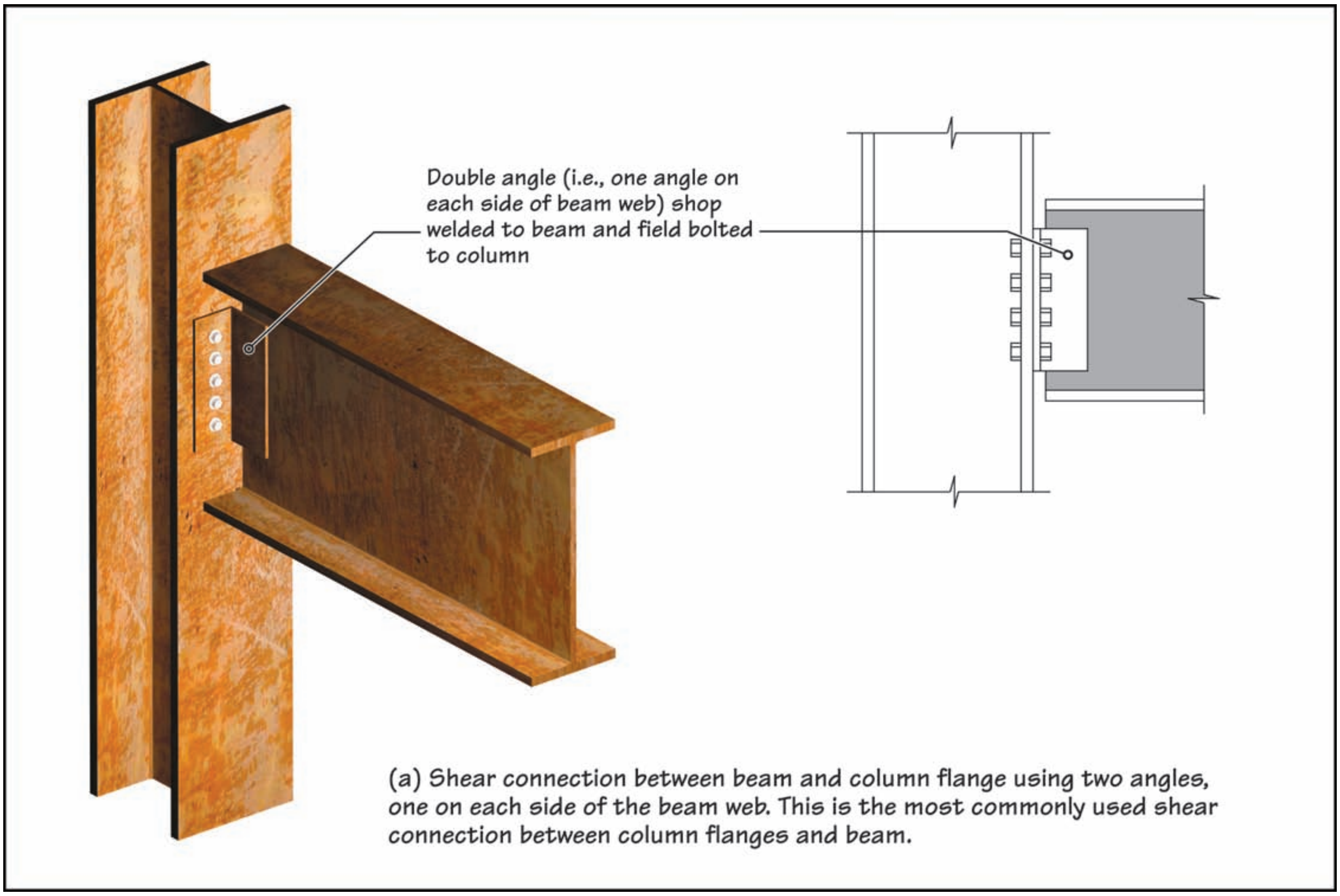
Bolting, on the other hand, is rapid, involves less-skilled labor, and can be accomplished without any surface cleaning. It is more suited to field conditions than welding because weather conditions have relatively little effect on bolting.

19.3 CONNECTIONS BETWEEN FRAMING MEMBERS

Structural steel connections are so varied and numerous that they cannot all be discussed here. Therefore, only the more commonly used connection types are illustrated:

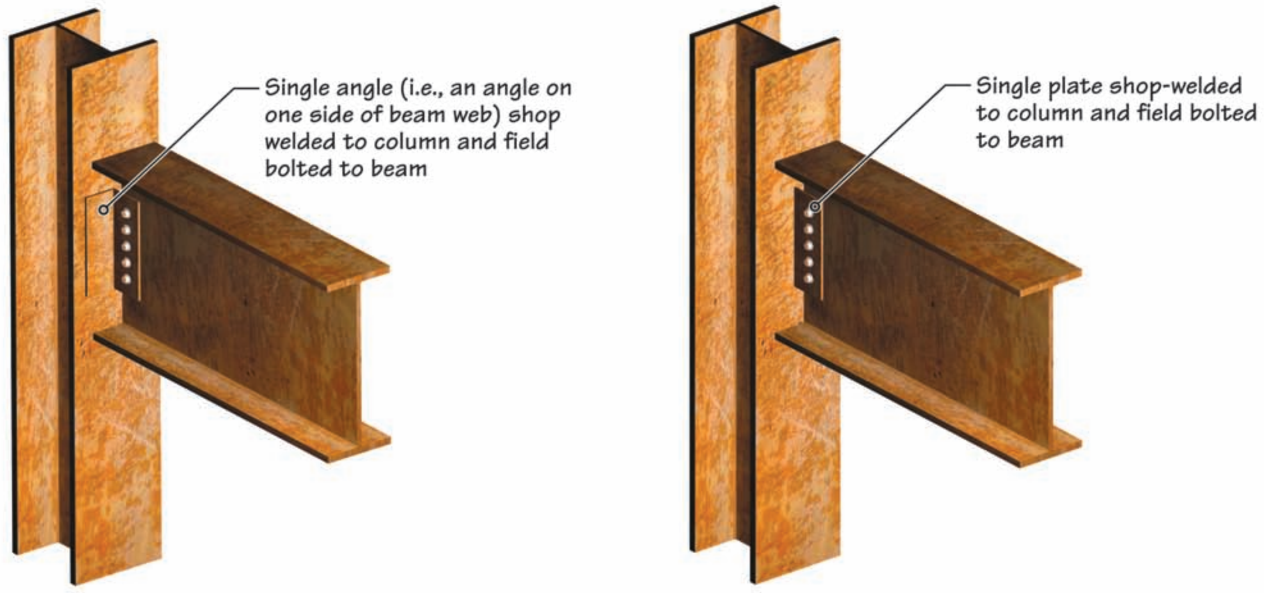
- Column-to-beam connections
- Beam-to-beam connections
- Column-to-column connections (i.e., column splice)

Each of these connections can be detailed in several ways. One of the major reasons for variations in the details for the same connection is the substitution of welds for bolts, or vice versa, particularly for the part of the connection that is shop produced. As Figures 19.10 to 19.13 show, part of the connection between members is made in the shop, and the remainder is completed in the field.


Double angle (i.e., one angle on each side of beam web) shop welded to beam and field bolted to column

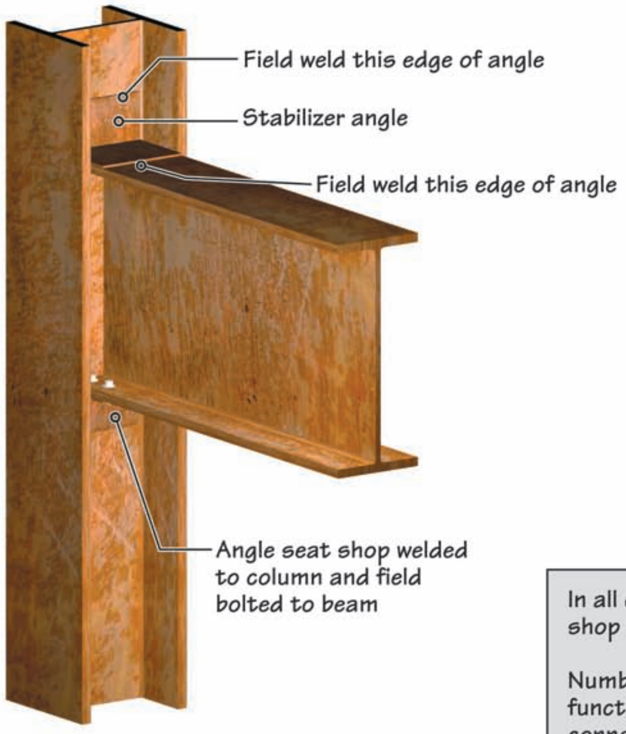
(a) Shear connection between beam and column flange using two angles, one on each side of the beam web. This is the most commonly used shear connection between column flanges and beam.

FIGURE 19.10 Typical column-beam shear (Type II) connections.


Single angle (i.e., an angle on one side of beam web) shop welded to column and field bolted to beam
Single plate shop-welded to column and field bolted to beam

(b) Shear connection between beam and column flange, using a single angle

(c) Shear connection between beam and column flange using a single plate, referred to as shear tab


Field weld this edge of angle
Stabilizer angle
Field weld this edge of angle
Angle seat shop welded to column and field bolted to beam

(d) Seated shear connection

In all connections, shop welding may be replaced by shop bolting.

Number and diameter of bolts in a connection are a function of the load to be transferred through the connection.

FIGURE 19.10 (*Continued*) Typical column-beam shear (Type II) connections.

Some fabrication shops prefer bolting to welding. Therefore, these shops generally use fully bolted connections. In other words, the shop-produced part of the connection is bolted, and because field bolting is preferred over field welding, the part of the connection completed in the field is also bolted. Fabrication shops that are better equipped for welding prefer shop-welded and field-bolted connections.

In addition to variations caused by substituting bolting for welding (and vice versa), the ease of erection governs the choice of connection details.

COLUMN-BEAM CONNECTIONS

The American Institute of Steel Construction (AISC) divides column-beam connections as follows:

- Rigid connection, also called *moment connection* or *AISC Type I connection*
- Simple connection, also called *shear connection* or *AISC Type II connection*
- Semirigid connection, also called *AISC Type III connection*

In practice, however, most connections are either simple or rigid connections. Therefore, only these two types are illustrated.

Column-Beam Simple (AISC Type II) Connections A simple connection is a flexible connection that allows the ends of the beam to rotate under the loads. (Although simple connections used in practice have some end restraint, i.e., moment resistance, the restraint is small and is, therefore, neglected.)

The most frequently used column-beam simple connection uses two angles that are shop welded to a beam and field bolted to a column flange (or web), as required, Figure 19.10(a). Where a single-angle connection is acceptable, it may be shop welded to the column and field bolted to the beam, Figure 19.10(b). A single angle may be replaced by a single plate, Figure 19.10(c).

A seated shear connection is well suited for connecting the beam with a column web, particularly if there is a beam on each side of the web, Figure 19.10(d). A seated shear connection consists of one angle at the bottom of the beam and the other at the top.

The top angle simply provides stability to the connection. Hence, it is called a *stabilizer angle*. To ensure that the stabilizer angle does not introduce moment resistance in the connection, it is generally field welded to both column and beam at the toes only (the edges away from the angle heel).

Column-Beam Rigid (AISC Type I) Connections Because a rigid connection must transfer tensile and compressive stresses between the beam and the column, the flanges of the beam are also connected to the column (in addition to the web connection). Observe from Figure 19.10 that in a shear connection, the flanges of the beam are not connected to the column.

One way of connecting beam flanges to the column is to weld them directly to the column using groove welds. This requires chamfered beam flanges, access holes, and backing bars, Figure 19.11(a). Backing bars prevent weld material from dripping down. To prevent weld material from flowing off the sides, runoff tabs are used, which are removed after the connection is made. Backing bars are, however, left in place. (In seismic zones, the backing bar at the bottom flange must be removed.)

Figure 19.11(b) shows another alternative to column-beam rigid connections, in which steel plates have been used to connect beam flanges to the column instead of direct welding the beam flanges to the column. These plates are referred to as *flange plates*.

BEAM-BEAM (OR GIRDER-BEAM) CONNECTIONS

Beam-to-beam connections, where one beam supports another beam, are fairly common in steel floors and roofs. These connections are generally simple connections and are similar to simple column-to-beam connections, Figure 19.12.

COLUMN SPLICES

Column splices are a necessity in a multistory building because of the limited length of steel members. Generally, column splices are provided every two stories. In a three-story building, however, the columns can be continuous—without splices.

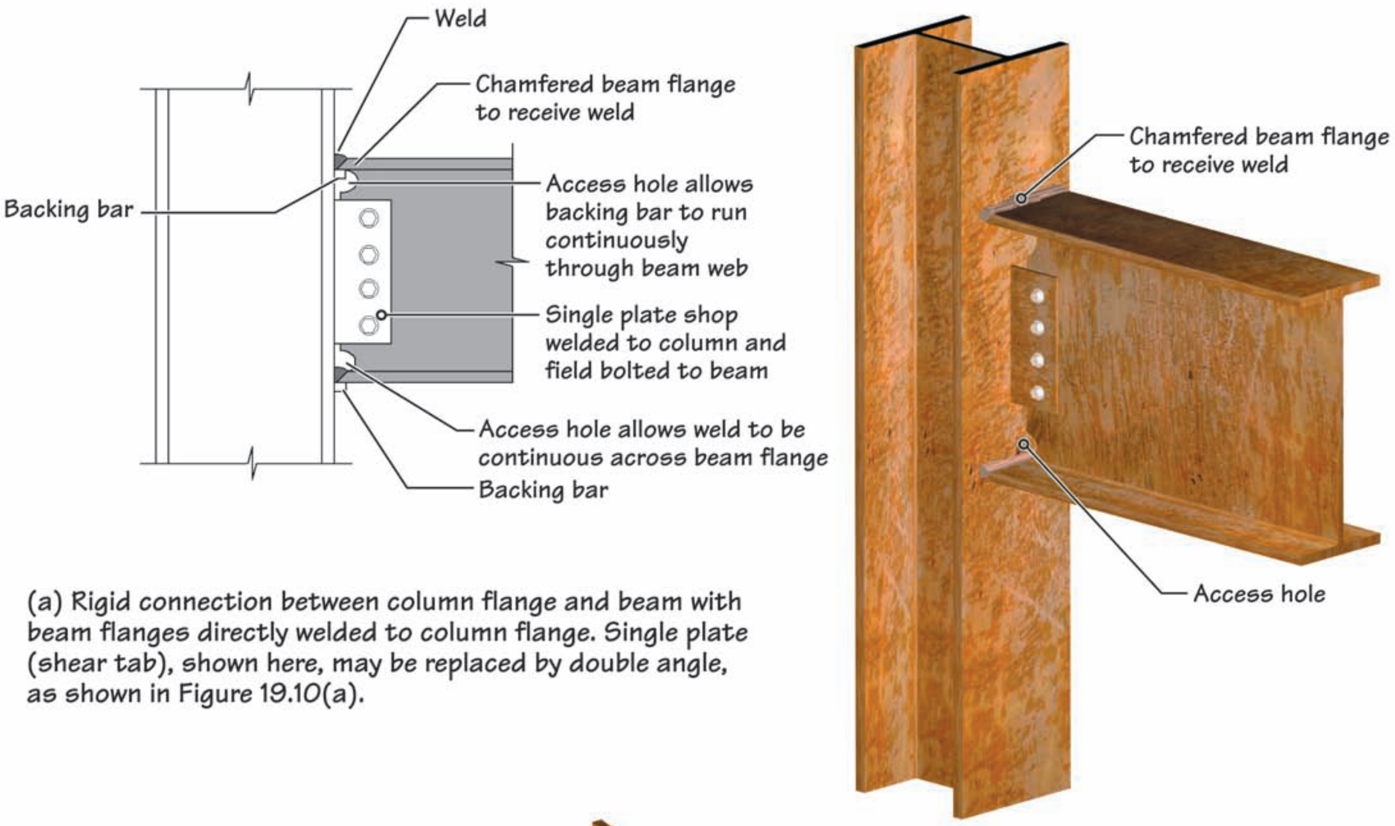
When provided, a column splice is located approximately 4 ft above the lower floor so that the erector can use the floor as a platform to make the connection. This is particularly important for the columns at perimeter locations, where the erector must use the lower column shaft to attach safety cables.

Where the lower and upper columns are of the same nominal dimensions, the upper column shaft bears on the lower column shaft and is connected to it with the help of flange plates, Figures 19.13(a) and (b). Flange plates may be shop welded to the lower column shaft and field bolted to the upper column shaft. However, an all-bolted connection is generally preferred. In a welded-bolted connection, the protruding flange plates can bend during transportation.

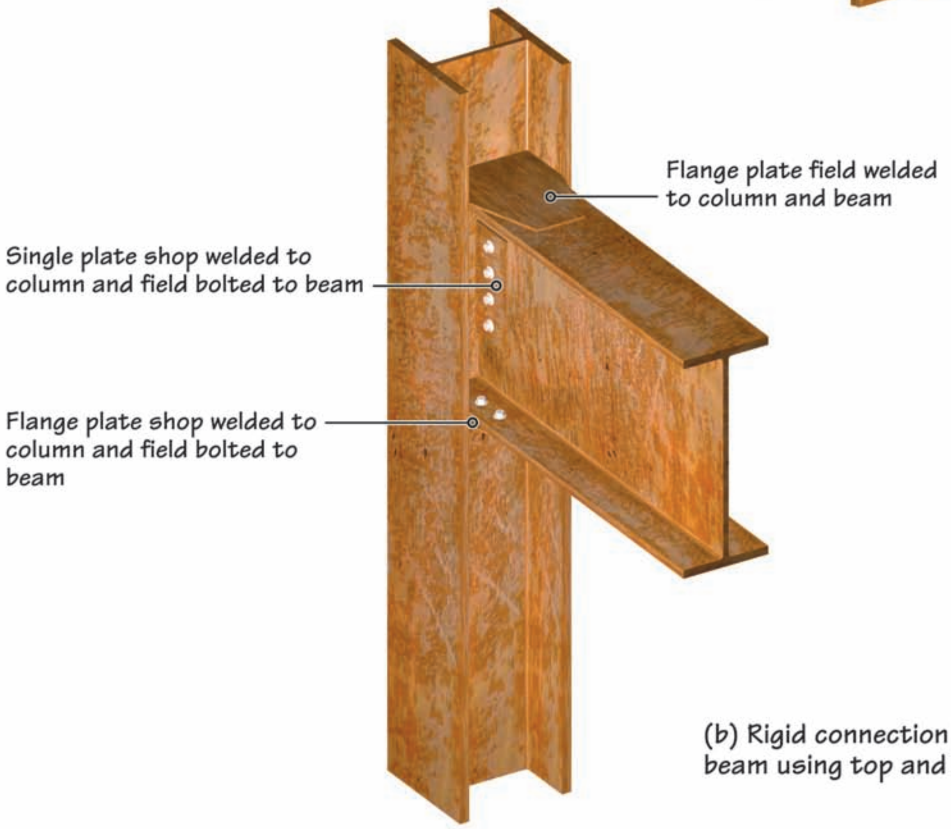
NOTE

Interchangeability of Terms Used for Steel Member Connections

With steel connections, the terms *simple connection*, *shear connection*, and *AISC Type II connection* are interchangeable. The terms *moment connection*, *rigid connection*, and *AISC Type I* are also interchangeable.


Weld
Chamfered beam flange to receive weld
Backing bar
Access hole allows backing bar to run continuously through beam web
Single plate shop welded to column and field bolted to beam
Access hole allows weld to be continuous across beam flange
Backing bar
Chamfered beam flange to receive weld
Access hole

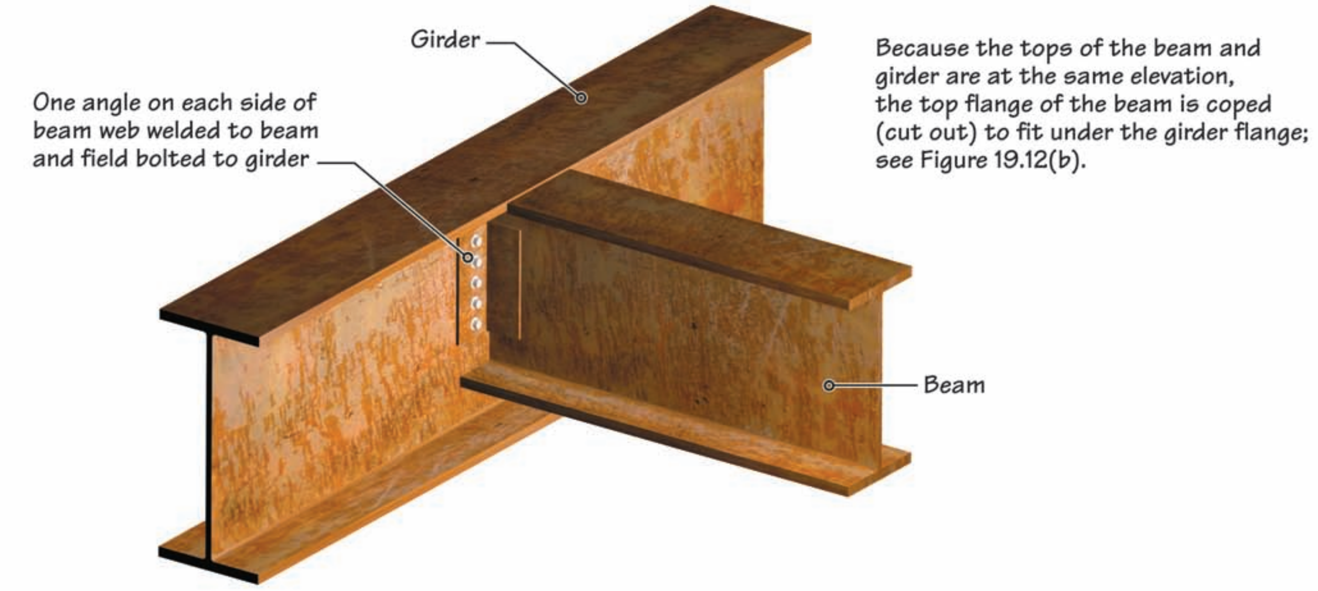
(a) Rigid connection between column flange and beam with beam flanges directly welded to column flange. Single plate (shear tab), shown here, may be replaced by double angle, as shown in Figure 19.10(a).


Flange plate field welded to column and beam
Single plate shop welded to column and field bolted to beam
Flange plate shop welded to column and field bolted to beam

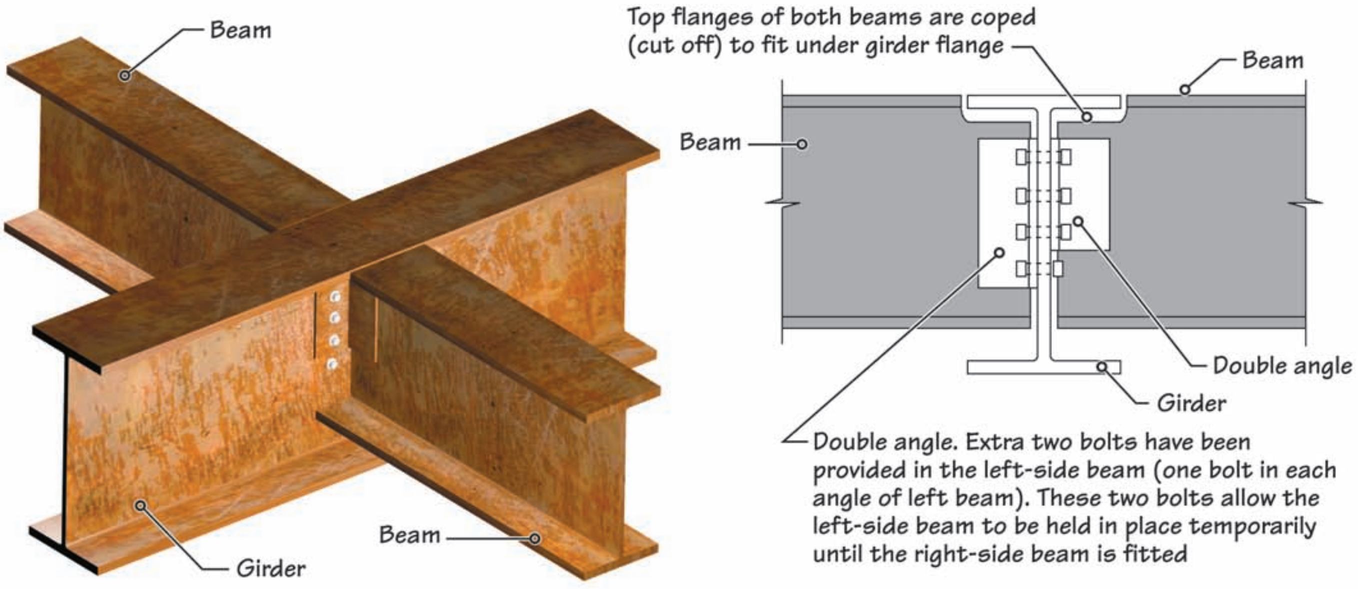
(b) Rigid connection between column web and beam using top and bottom flange plates

FIGURE 19.11 Typical column-beam rigid connections.

If the upper and lower columns are of slightly different nominal dimensions, a flange-plated connection may still be used because it is not necessary that the upper column must bear fully on the lower column. However, if the upper and lower columns are significantly different in dimensions, a butt plate and flange plates are used at the connection, Figure 19.13(c).


Girder
One angle on each side of beam web welded to beam and field bolted to girder
Because the tops of the beam and girder are at the same elevation, the top flange of the beam is coped (cut out) to fit under the girder flange; see Figure 19.12(b).
Beam

(a) Girder-beam connection with beam supported on one side of girder, using double angles for connection. Angles are shop welded to beam and bolted to girder.


Beam
Top flanges of both beams are coped (cut off) to fit under girder flange
Beam
Beam
Double angle
Girder
Double angle. Extra two bolts have been provided in the left-side beam (one bolt in each angle of left beam). These two bolts allow the left-side beam to be held in place temporarily until the right-side beam is fitted
Beam
Girder

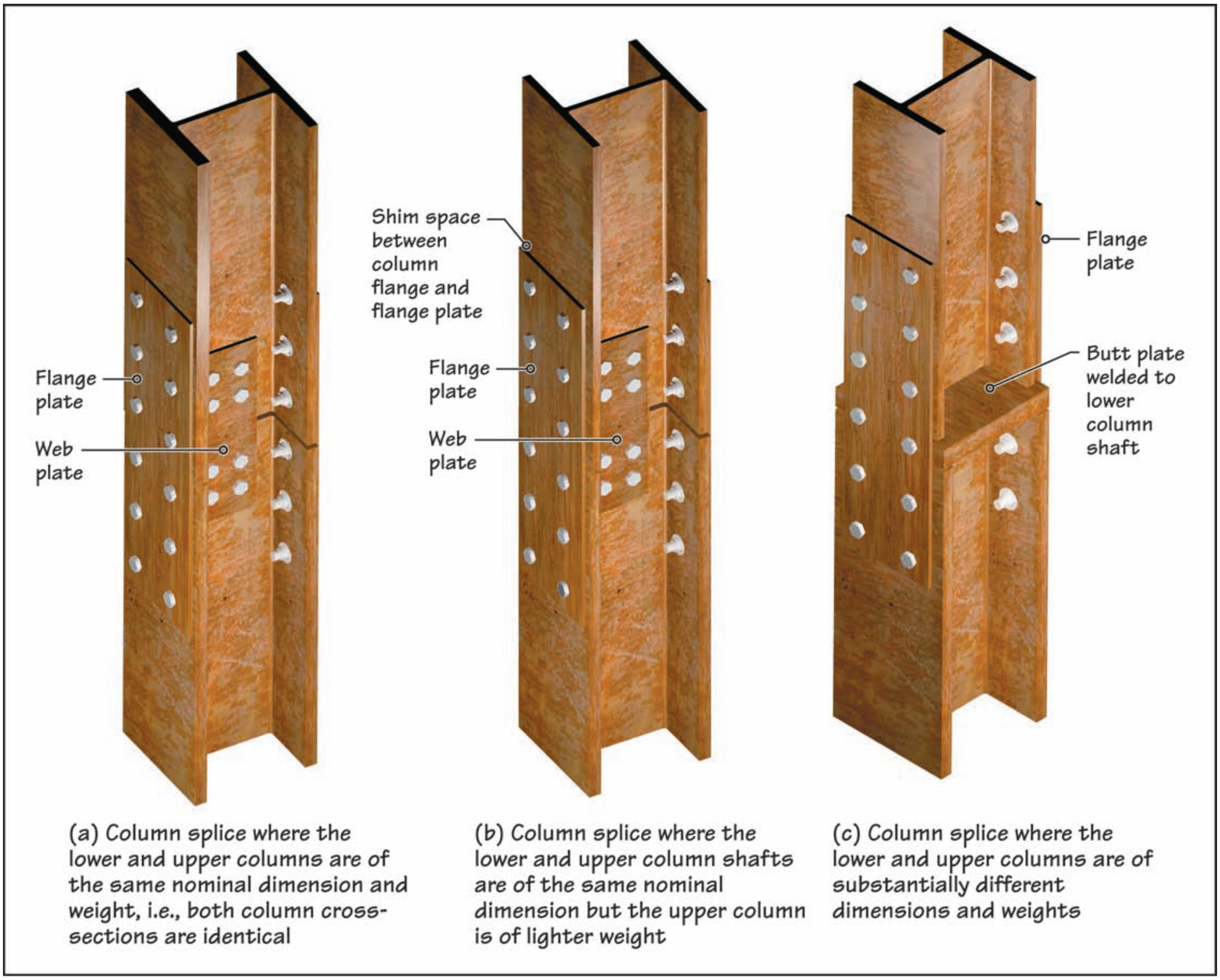
(b) Girder-beam connection with beam supported on each side of girder, using double angles for connection. Angles are welded to beams and field bolted to girder.

FIGURE 19.12 Typical girder-beam (shear) connections.

19.4 STEEL DETAILING AND FABRICATION

Unlike masonry and site-cast concrete construction, in which various components, such as walls, columns, and beams, are constructed at the site, structural steel components are brought to the site in a prefabricated and finished state, ready for erection and assembly. There is very little cutting, notching, and drilling of components at the site.

The fabrication of ready-to-erect components is done in a steel fabrication shop. A fabricator, who generally works as a subcontractor to the general contractor, first prepares a set of shop drawings based on the project's contract documents. The shop drawings delineate every component of the building with its precise dimensions.


Flange plate
Web plate
Shim space between column flange and flange plate
Flange plate
Web plate
Flange plate
Butt plate welded to lower column shaft

(a) Column splice where the lower and upper columns are of the same nominal dimension and weight, i.e., both column cross-sections are identical

(b) Column splice where the lower and upper column shafts are of the same nominal dimension but the upper column is of lighter weight

(c) Column splice where the lower and upper columns are of substantially different dimensions and weights

FIGURE 19.13 Typical column splices. Column ends are milled smooth giving full end bearing to achieve proper transfer of loads.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The preliminary framing layout of a building is generally prepared by the
- **a.** project's structural engineer.
- **b.** project architect.
- **c.** general contractor.
- **d.** steel fabricator.
- **e.** none of the above.

2. The preliminary framing layout of a steel-frame building is generally presented in
- **a.** three-dimensional view.
- **b.** elevation view.
- **c.** plan view.
- **d.** all of the above.
- **e.** none of the above.

3. If the floor of a steel-frame building has primary, secondary, and tertiary components, the tertiary components consist of
- **a.** W-section beams.
- **b.** steel joists.
- **c.** joist girders.
- **d.** any one of the above.
- **e.** none of the above.

4. If the floor of a steel-frame building has only primary and secondary components, the secondary components consist of
- **a.** W-section beams.
- **b.** steel joists.
- **c.** joist girders.
- **d.** floor deck.
- **e.** none of the above.

5. If the floor of a steel-frame building has primary, secondary, and tertiary components, the secondary components consist of
- **a.** W-shape beams.
- **b.** steel joists.
- **c.** steel joist girders.
- **d.** any one of the above.
- **e.** (a) or (b).

6. Which of the following is not an ASTM designation for steel bolts?
- **a.** A325 bolts
- **b.** A307 bolts
- **c.** A490 bolts
- **d.** A507 bolts

7. A snug-tight connection between framing members is obtained by
- **a.** welding the members together using arc welding.
- **b.** welding the members together using gas welding.
- **c.** bolting the members and tightening them with a spud wrench.
- **d.** bolting the members and tightening them with a spud wrench using full force.
- **e.** none of the above.

8. A slip-critical connection between framing members is obtained by
- **a.** welding the members together using arc welding.
- **b.** welding the members together using gas welding.
- **c.** bolting the members and tightening them with a spud wrench.
- **d.** bolting the members and tightening them with a spud wrench using full force.
- **e.** none of the above.

9. Field bolting of steel members is generally preferred over field welding.
a. True
b. False

10. A shear connection between a steel beam and a steel column is also called
a. a simple connection.
b. a rigid connection.
c. a semirigid connection.
d. an AISC Type I connection.
e. none of the above.

11. A shear connection between a steel beam and a steel column can be made without connecting beam flanges to the column.
a. True
b. False

12. A rigid connection between a steel beam and a steel column can be made without connecting beam flanges to the column.
a. True
b. False

13. In a multistory steel-frame building, the columns are generally spliced
a. every four floors.
b. every three floors.
c. every two floors.
d. every floor.
e. none of the above.

14. In connecting the upper-column shaft with a lower-column shaft in a multistory steel-frame building, we generally require
a. four flange plates.
b. three flange plates.
c. two flange plates.
d. one flange plate.

15. In a column splice detail, a butt plate is required when
a. the upper-story column is much smaller in height than the lower-story column.
b. the upper-story column is much larger in height than the lower-story column.
c. the upper-story column is the same height as the lower-story column.
d. the upper-story column has the same cross-sectional dimensions as the lower-story column.
e. none of the above.

Each connection is fully detailed, giving the dimensions of all connection angles and plates, including the number of holes, bolt diameters, size and types of welds, and so on. The drawings also distinguish between shop and field welds. The type of bolted connection (snug-tight or slip-critical) is also identified. If a member is required to be cambered (based on the contract documents), the amount of camber is indicated on the shop drawings.

As described in Chapter 1, the purpose of the shop drawings is to help the fabricator fabricate various components so that they can be assembled at the site with ease and on a predetermined schedule.

STEEL DETAILING

For most buildings, the design and detailing of connections between components (such as those shown in Figures 19.10 to 19.13) are prepared by the fabricator based on the framing plans and other information provided in the project's structural drawings. Leaving connection detailing to the fabricator allows the fabricator to use the details that are most economical and best suited for erection, scheduling, and the peculiarities of the site. Where details are aesthetically significant, the fabricator must conform to the architectural and structural requirements of the project.

Some fabricators have an in-house detailing staff. Most fabricators, however, subcontract the work to an independent steel detailer. Structural steel detailing is both a science and an art because the details must not only be able to withstand the forces (as required by the engineer's drawings) but also be economical, be easy to erect, and suit the fabrication shop's capabilities and resources.

NOTE

Cambering

Camber is generally provided in floor beams to counter their deflection under dead loads. Because dead-load deflection is downward, the camber is an upward curvature in the beam. It is provided in the fabricator's shop.

The purpose of camber is to ensure that the beam becomes flat under dead loads and will be subjected to deflection only under live loads. If camber is not provided, the beam will have a larger deflection due to the combined dead-load and live-load deflections.

Cambering adds to the cost of the beam, but to obtain the same deflection reduction without cambering, the beam size must be increased, which is more expensive. However, camber should not be overspecified. Overspecification of camber not only costs more, but it may leave the top of the shear studs sticking out of the concrete topping.

Generally, camber is calculated to counter the deflection created by two-thirds to three-quarters of the dead load on the beam.

ORDERING MATERIALS FOR FABRICATION

After the shop drawings are completed, they are reviewed first by the general contractor and then by the project architect and structural engineer. Because the modifications expected from the review process are generally minor, the fabricator orders the structural steel sections from the rolling mills while the review of shop drawings is in progress.

Most rolling mills need sufficient lead time to deliver the material, particularly the heavier structural steel sections. This is because a rolling mill rolls a certain section (and a steel grade) for a few days; then the rollers are changed to produce a different section (Figure 18.4). Thus, a given section is rolled at intervals that may range from weeks to months. Therefore, a rolling mill generally rolls a batch containing different sections on order. To hold various grades, sections, and lengths in the mill's stock waiting to receive an order is too uneconomical for most mills.

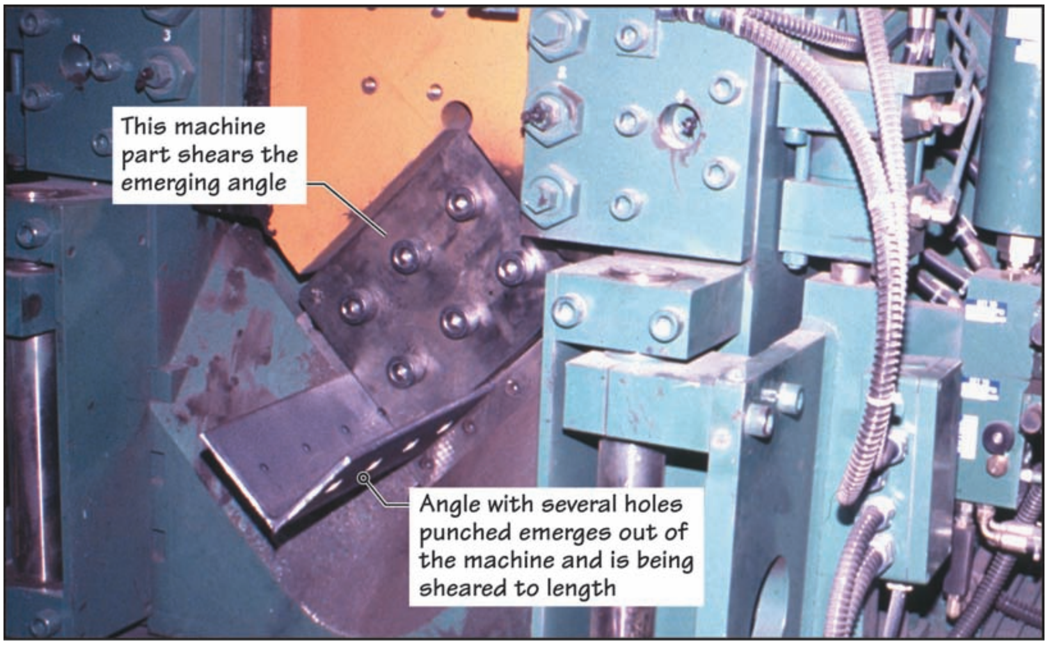

This machine part shears the emerging angle
Angle with several holes punched emerges out of the machine and is being sheared to length

FIGURE 19.14 A computer-aided plate and angle punching machine cuts plates and angles to the required size and drills holes of the required diameters and spacings without any manual labor. Photo taken at the Irwin Steel Fabrication Plant, Justin, Texas.

A fabricator may order heavy sections (for columns and beams) cut to the required lengths by the mill. On the other hand, the fabricator may opt to cut the sections to lengths from standard mill lengths in the shop if that is more economical. Standard lengths are generally 30 ft, 35 ft, 40 ft, and so on, up to 60 ft. Length greater than 60 ft may be available as a special order. Smaller sections, such as plates and angles, are always cut by the fabricator.

It is important to realize that structural sections with exactly the same specified dimensions and weight may not, in reality, be of the same dimensions. Wear of the rollers, thermal distortion of hot cross sections and their subsequent cooling, and several other factors cause the dimensions of the sections with the same specifications to be slightly different. Steel detailers and fabricators recognize this fact and provide the required connection and erection tolerances.

FABRICATION

Most large steel-fabrication shops are semiautomated, that is, computer assisted, which makes the fabrication process not only precise but also quick. Figure 19.14 shows a typical angle-shearing machine that shears the angles to size and drills holes of the required diameters and spacings without any manual labor. Whereas lighter sections, such as plates and angles, are sheared, heavier steel sections, such as beams and columns, are sawed to desired length by semi-automated or fully automated saws, Figure 19.15.

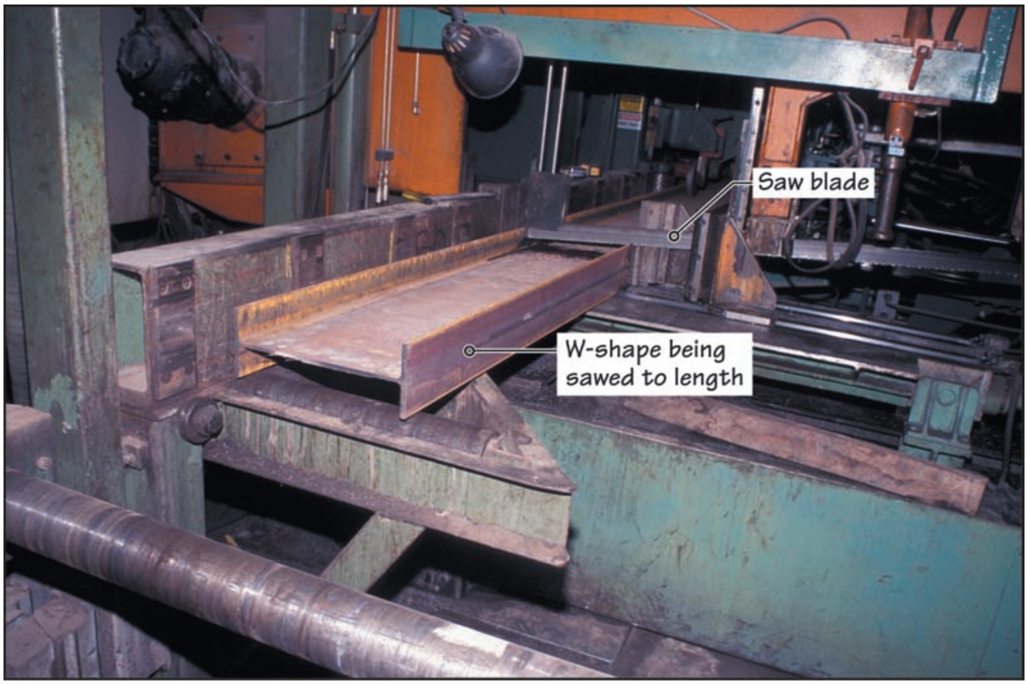


FIGURE 19.15 A computer-aided band saw cuts heavy steel members to size. The machine is versatile enough to make skew cuts instead of a right-angle cut, as shown here. Photo taken at the Irwin Steel Fabrication Plant, Justin, Texas.

Welding in most fabrication shops is carried out manually. For long, continuous lines of welds or repetitive welding, an automated welding system is used.

Most structural steel members do not require any surface preparation, such as blast-cleaning or a prime coat. However, if the steel has developed loose mill scale because of its extended exposure to weather, it should be blast cleaned, particularly if it is to be treated with spray-on fire protection or intumescent paint or galvanized. Steel components that are to be finished with paint generally require a shop coat of primer.

As the components are being fabricated, they are identified by marks that help further fabrication and erection. Unless dispatched to the construction site immediately on fabrication, the fabricated components are stored in the fabricator's shed. The storage is planned in a way that allows easy retrieval for delivery to the site in predetermined batches.

19.5 STEEL ERECTION

The erection of the structural steel frame at the site may be performed by the fabricator or by a separate erection company. In most cases, the general contractor will seek separate bids for fabrication and erection. If the fabricator, selected on the basis of a competitive bid for fabrication, also submits a competitive bid for erection, the fabrication and erection may be done by the same organization. If not, the erection contract may be given to a different company. Fabrication and erection by the same entity is obviously preferred.

Steel frame erection begins with the erection of columns, Figure 19.16, using a crane. For a small building, a mobile crane on rubber tires is generally adequate. For a large building, a tower crane is needed in addition to one or more mobile cranes, Figure 19.17. Generally, a tower crane is built over the foundations of an elevator shaft. Climbing cranes, secured to the building's columns, can also be used. In that case, a climbing crane climbs up the columns as the building's height increases. These columns are specially engineered and provided with special attachment points.

Structural steel columns are anchored to the foundations through anchor bolts. The anchor bolts are set into column footings before footing concrete is placed. The bolts are supplied by the fabricator but embedded into the footings by the general contractor per the fabricator's details.

A steel base plate is shop welded to the column bottom with predrilled holes to penetrate the anchor bolts. Columns are leveled to ensure that they are plumb, which can be done in a number of ways. One method uses leveling bolts under the base plate, Figure 19.18(a).

A space (minimum 2 in.) between the top of the footing and the bottom of the base plate is needed. After the column has been leveled and the frame squared and stabilized, this space is filled with Portland cement and sand grout, Figure 19.18(b). For a wide base plate (generally more than 24 in.), grout holes in the base plate may also be needed to ensure full bearing after grouting. The grout is packed under the base plate using a trowel.

The other alternative is to level a relatively thin steel plate of the same size as the base plate using high-strength plastic shims under the plate. After the plate has been leveled, the steel column is placed over the plate and bolted into place, Figure 19.19. A space (minimum 1 in.) is

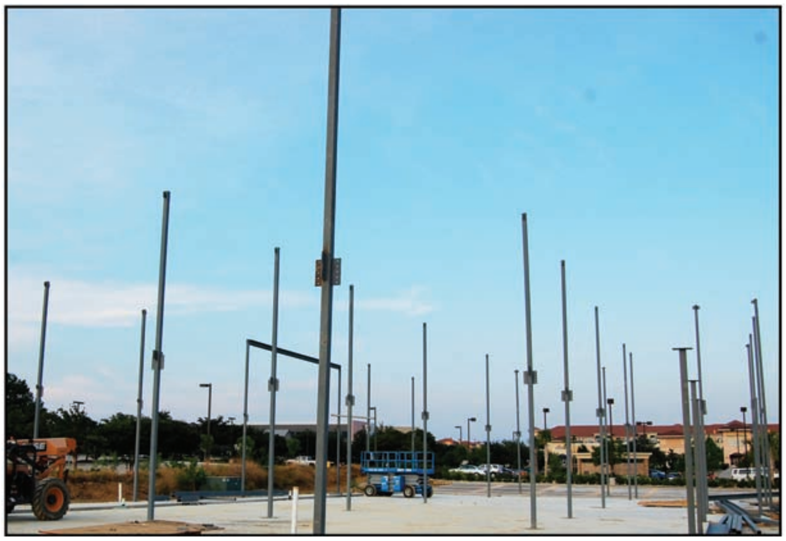


FIGURE 19.16 The erection of a steel frame begins with the erection of columns. The columns, with their shop-welded base plates, are anchored to the bolts embedded in the foundations (see Figures 19.18 and 19.19) by the general contractor as per the fabricator's details. In a multistory building, each column shaft is generally two-stories tall.

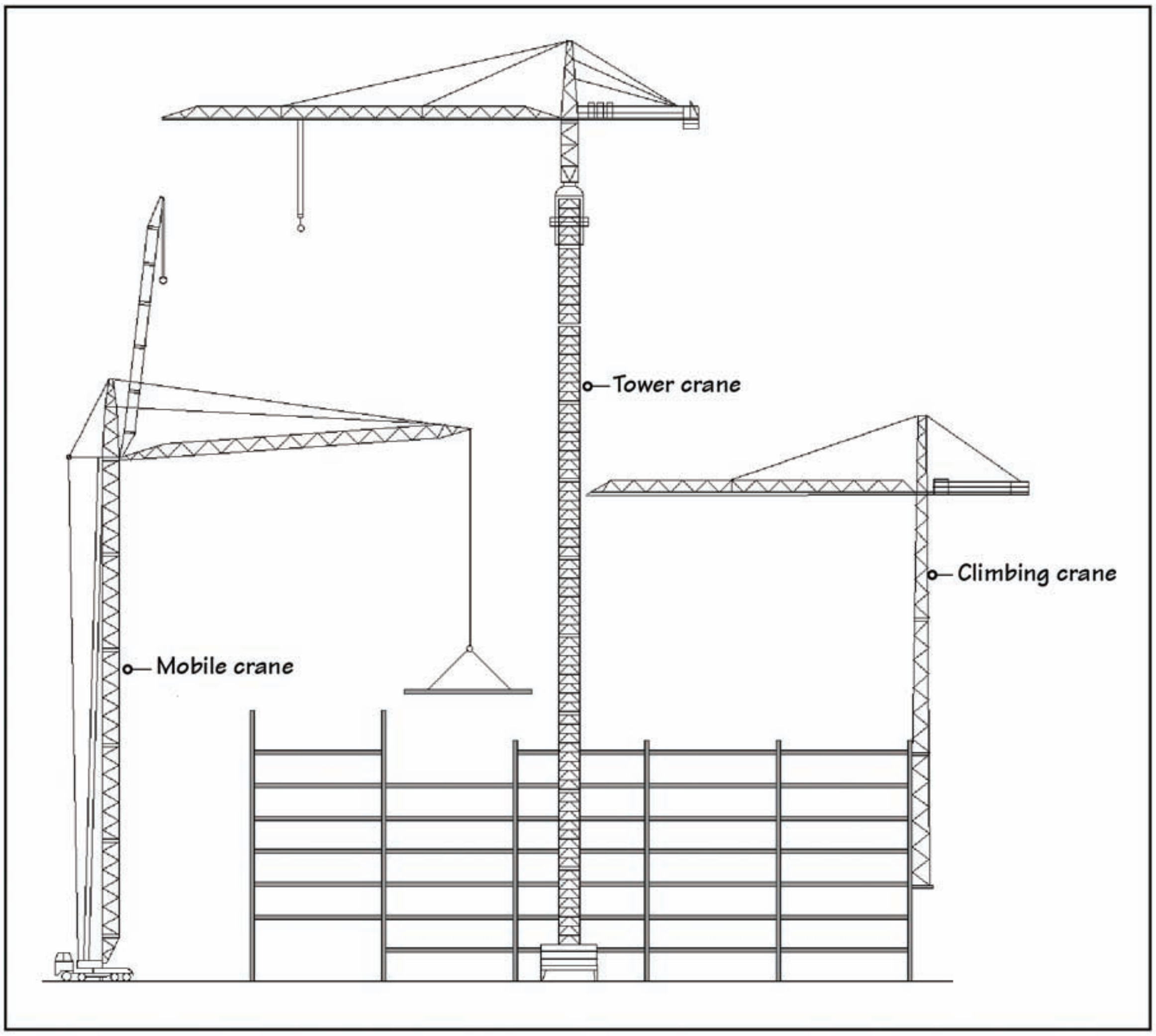

Tower crane
Climbing crane
Mobile crane

FIGURE 19.17 Some of the various types of cranes used in steel frame erection.

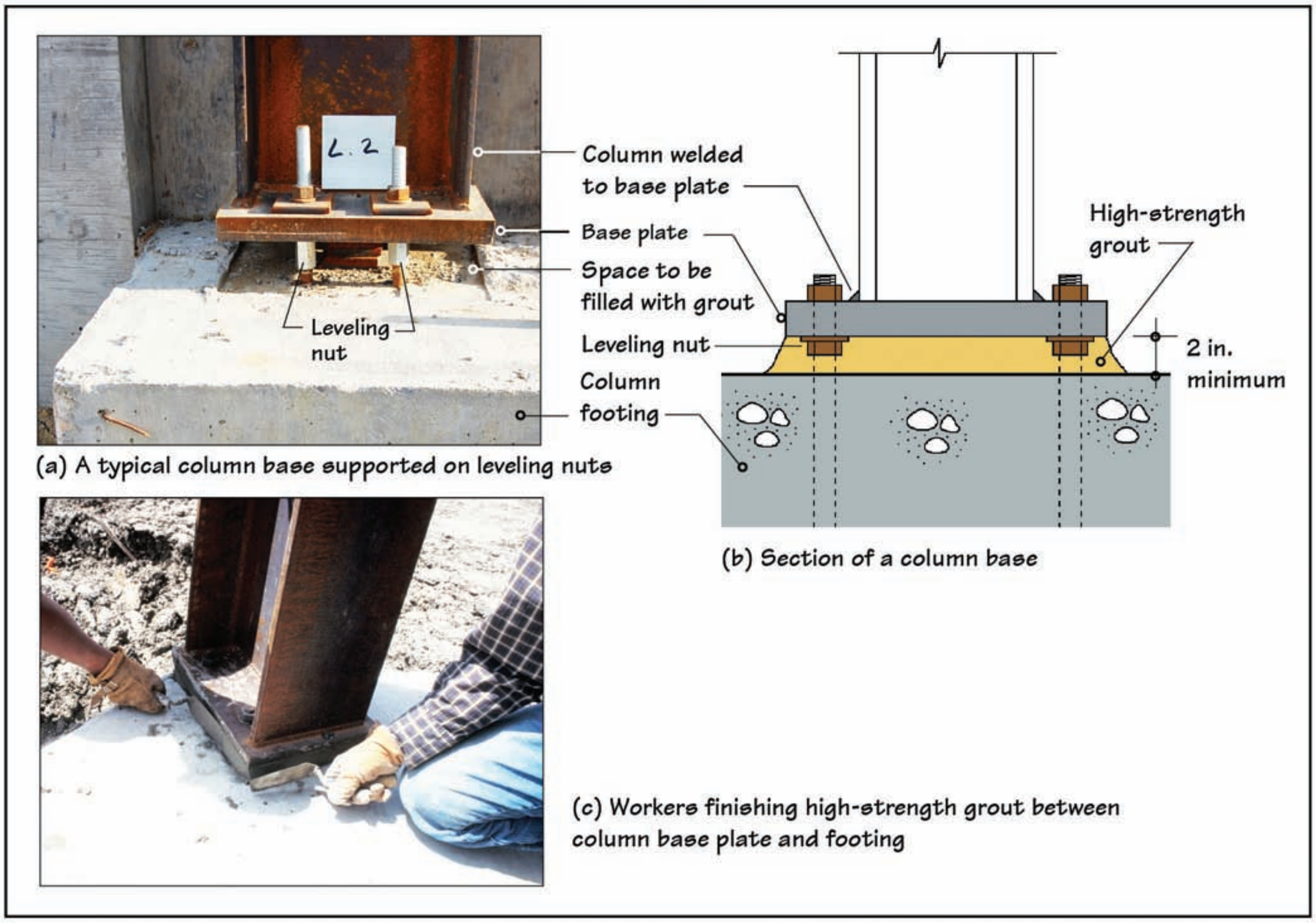

L. 2
Column welded to base plate
Base plate
Space to be filled with grout
Leveling nut
Leveling nut
Column footing
(a) A typical column base supported on leveling nuts
High-strength grout
2 in. minimum
(b) Section of a column base
(c) Workers finishing high-strength grout between column base plate and footing

FIGURE 19.18 Leveling a column base plate using leveling nuts.

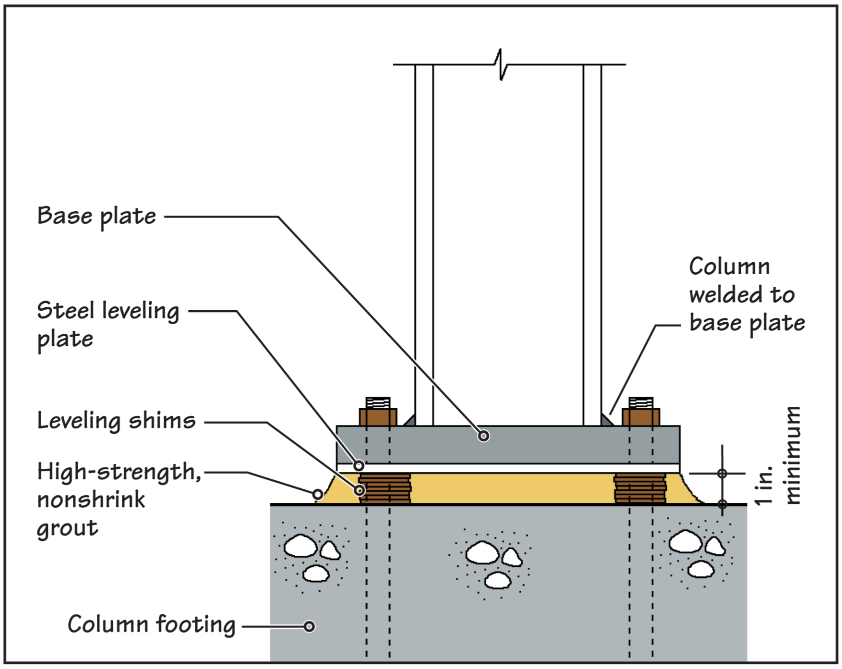

Base plate
Steel leveling plate
Leveling shims
High-strength, nonshrink grout
Column footing
Column welded to base plate
1 in. minimum

FIGURE 19.19 Leveling a column base plate using high-strength plastic shims placed under a thin steel plate.

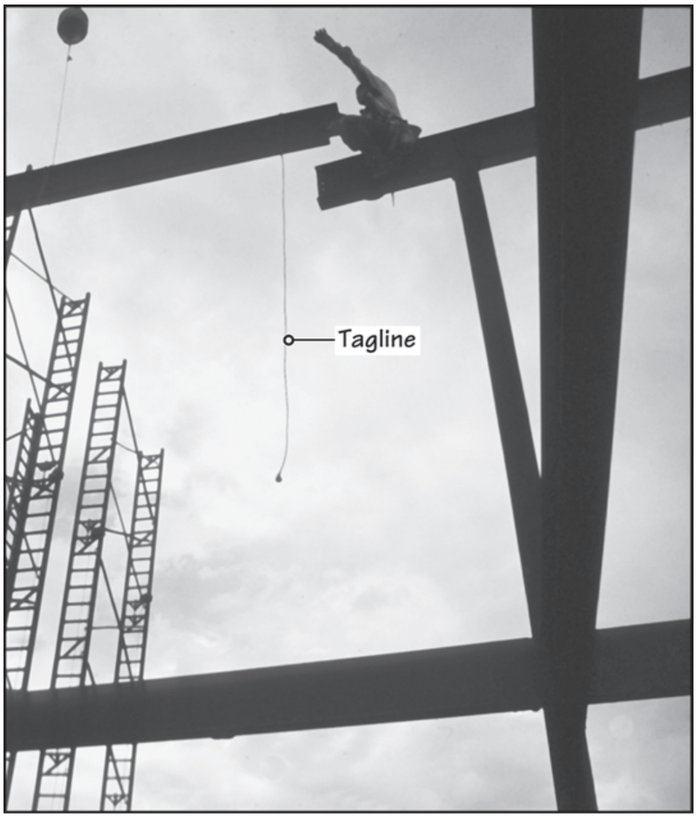


FIGURE 19.20 A steel erector (with his body harness tied to the beam on which he sits) maneuvers the new beam into position, initially using the rope attached at the end of the beam and later by hand. The rope is referred to as a *tagline* in erection vernacular.

needed between the top of the footing and the bottom of the base plate. This space is grouted in the same way as shown in Figure 19.18(b), but the grout must be high-strength, nonshrink grout.

After a few columns for the first tier have been erected, beams are connected to them. The erection of framing members is a coordinated effort between the crane operator and the erectors. The erector must guide the member into position, initially through a tagline and finally by hand, Figure 19.20.

Certain connections may require some forced alignment between the holes in the parts to be connected. Crowbars, hammers, drift pins, and so on, may be used to bring members into alignment, Figure 19.21.

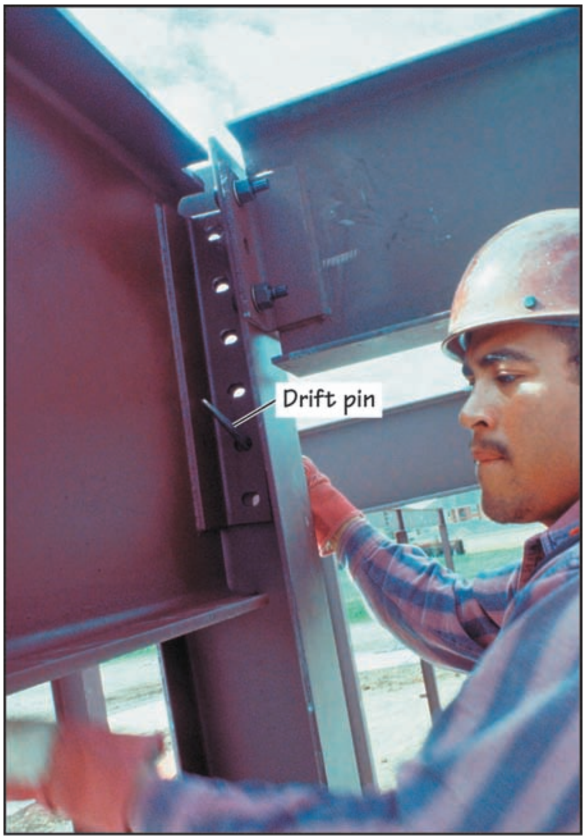


FIGURE 19.21 Generally, members at a connection are forced to align. In this image, a drift pin has been used to make the alignment. In some connections, crowbars or hammers may have to be used.

The initial connection between members is made using some of the bolts in the connection. After most of the members have been placed in position, the remaining bolts are installed and the connection is completed by hand tightening the bolts. Finally, an impact wrench is used in case of slip-critical connections.

The placement of beams for a tier is followed by floor and roof decking. The installation of decking is done by the general contractor or the erector, depending on the contract.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

16. The fabrication of structural steel components is done based on
- **a.** architectural construction drawings.
- **b.** structural construction drawings.
- **c.** both (a) and (b).
- **d.** shop drawings.
- **e.** none of the above.

17. Details of connections between structural steel members are prepared by the
- **a.** architect.
- **b.** structural engineer.
- **c.** both (a) and (b).
- **d.** general contractor.
- **e.** none of the above.

18. The erection of structural steel members is generally done by the
- **a.** general contractor.
- **b.** structural engineer.
- **c.** American Institute of Steel Construction.
- **d.** steel detailer.
- **e.** none of the above.

19. The installation of a floor or roof deck is done by the
- **a.** general contractor.
- **b.** erector.
- **c.** manufacturer of the deck.
- **d.** (a), (b), or (c).
- **e.** (a) or (b).

20. Camber refers to
- **a.** downward deflection of a beam.
- **b.** upward deflection of a beam to counter downward deflection by a live load.
- **c.** upward deflection of a beam to counter downward deflection by a dead load.
- **d.** upward deflection of a beam to counter downward deflection by a dead load plus a live load.
- **e.** none of the above.

21. In connecting a steel column to concrete foundations, anchor bolts are used. These bolts are embedded into the foundation by
- **a.** the general contractor.
- **b.** the fabricator.
- **c.** the erector.
- **d.** a specialized bolt-embedding outfit.
- **e.** none of the above.

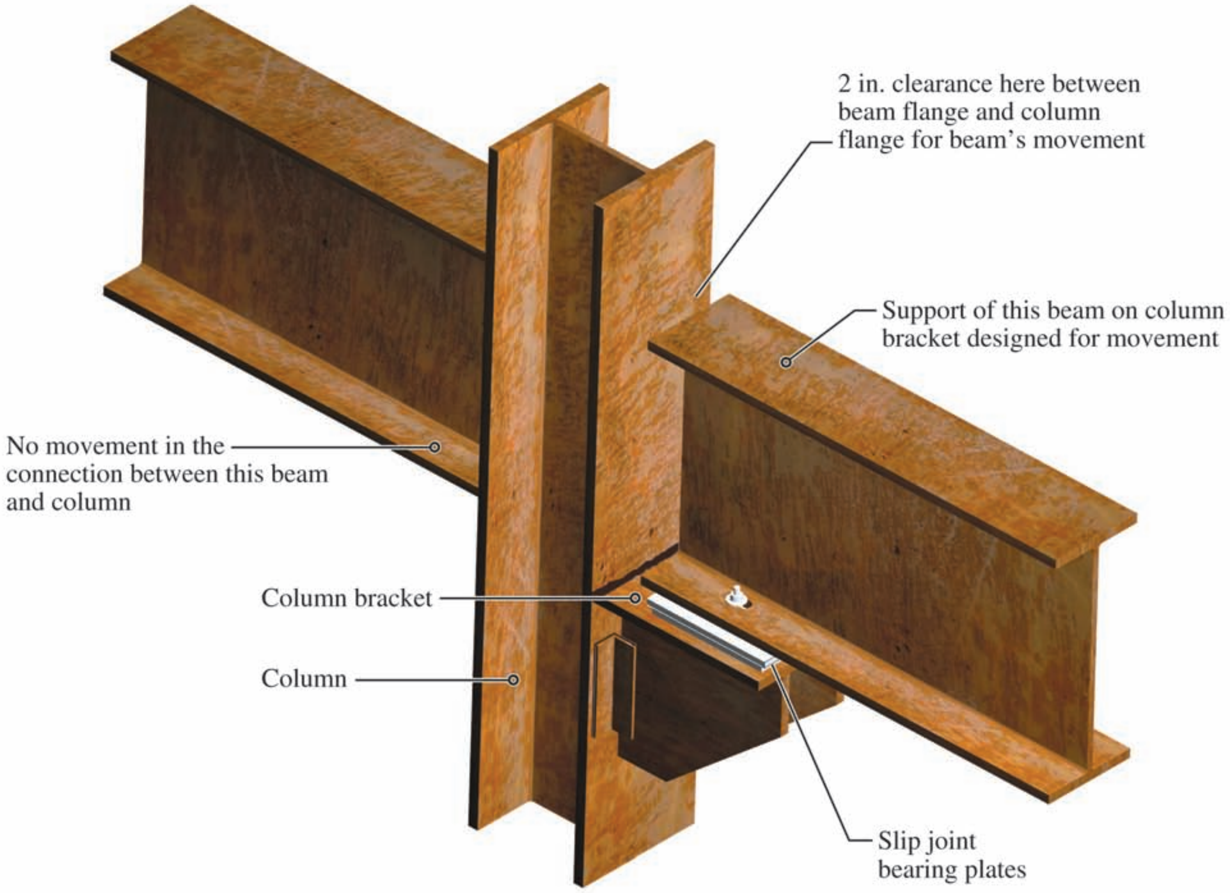
22. A steel column may or may not need a base plate at the bottom.
- **a.** True
- **b.** False

23. To level a column so that it is plumb,
- **a.** steel shims are used.
- **b.** high-strength plastic shims are used.
- **c.** leveling bolts are used.
- **d.** any one of the above.
- **e.** none of the above.

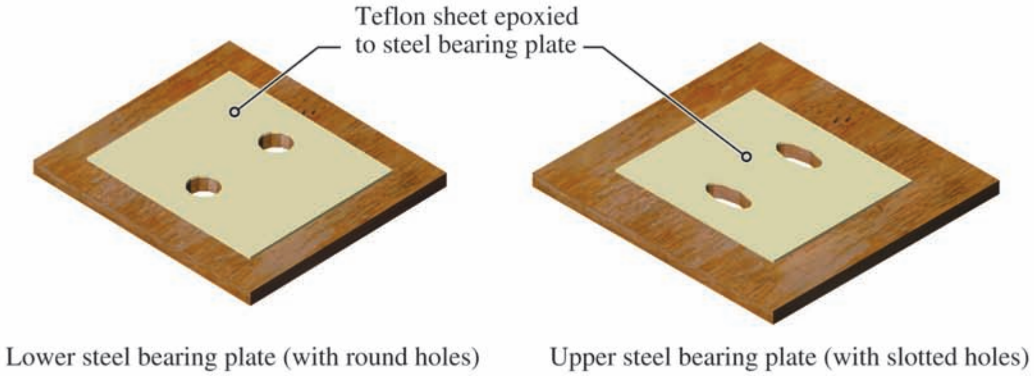
A Building Separation Joint in a Steel-Frame Building

As discussed in Section 9.2, continuous building separation joints are required in many buildings. A preferred method is to use two columns and two beams at the joint. Often for the sake of economy, however, a single column with two beams is used. Figure 19.22 explains the construction of such a joint in a building with W-shape columns and beams. (See Chapter 23 for a similar detail in a reinforced concrete building.)

Details of a building separation joint for a single-story building, consisting of joists and joist girders, are shown in Figure 19.23.


2 in. clearance here between
beam flange and column
flange for beam's movement
Support of this beam on column
bracket designed for movement
No movement in the
connection between this beam
and column
Column bracket
Column
Slip joint
bearing plates

(a) SLIP-JOINT (STEEL BEARING PLATE ASSEMBLY)
This assembly consists of two steel bearing plates. Each bearing plate (shown below) is factory epoxied to a Teflon sheet. The lower bearing plate is welded to column bracket and consists of two round holes. The upper bearing plate consists of slotted holes. The slotted holes allow the beam to slide over the lower bearing plate. The upper bearing plate is slightly larger than the lower bearing plate, which produces a gap at the end between plates to allow it to be filled with an elastomeric sealant. The sealant protects Teflon sheet from being damaged by dust and other desposits.

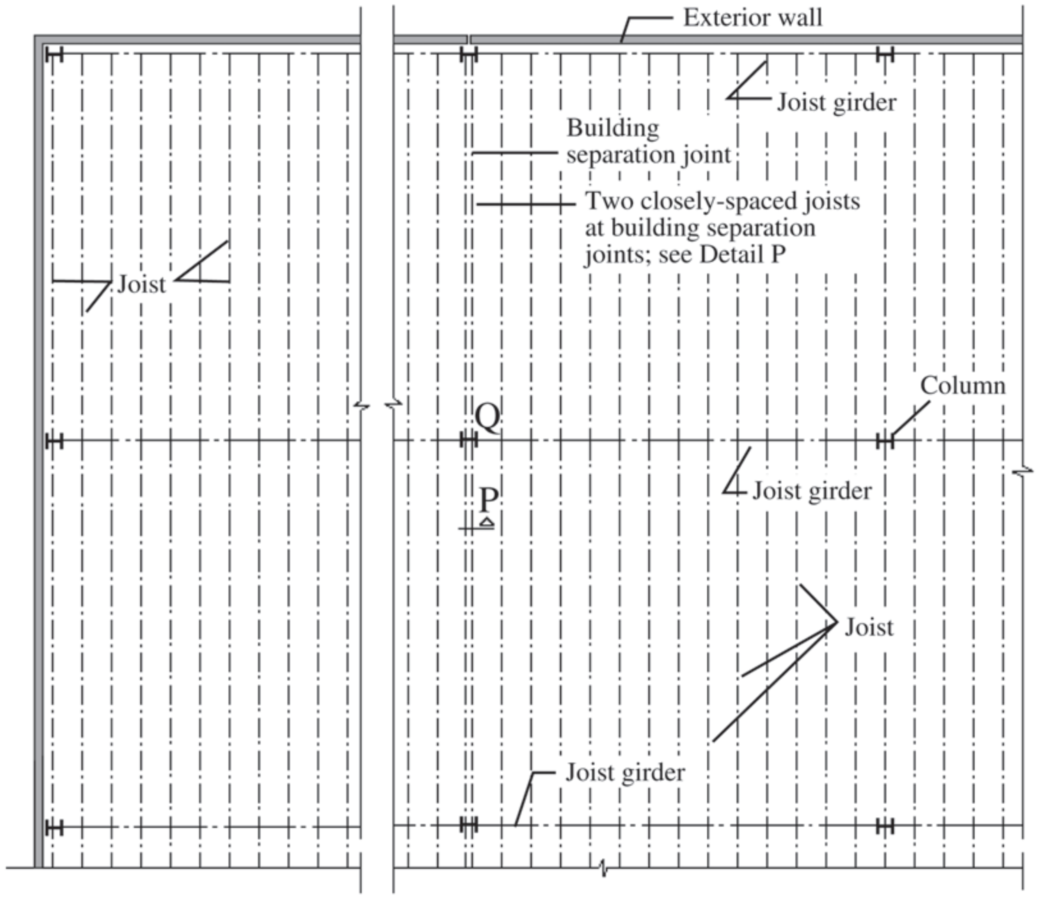

Teflon sheet epoxied
to steel bearing plate
Lower steel bearing plate (with round holes)
Upper steel bearing plate (with slotted holes)

(b) STEEL BEARING PLATES
Although the plates have been shown separated from each other, they are placed over each other with Teflon surfaces in contact. (For properties of Teflon sheet, see Expand Your Knowledge, "Building a Separation Joint in a Sitecast Concrete Building" in Chapter 23)

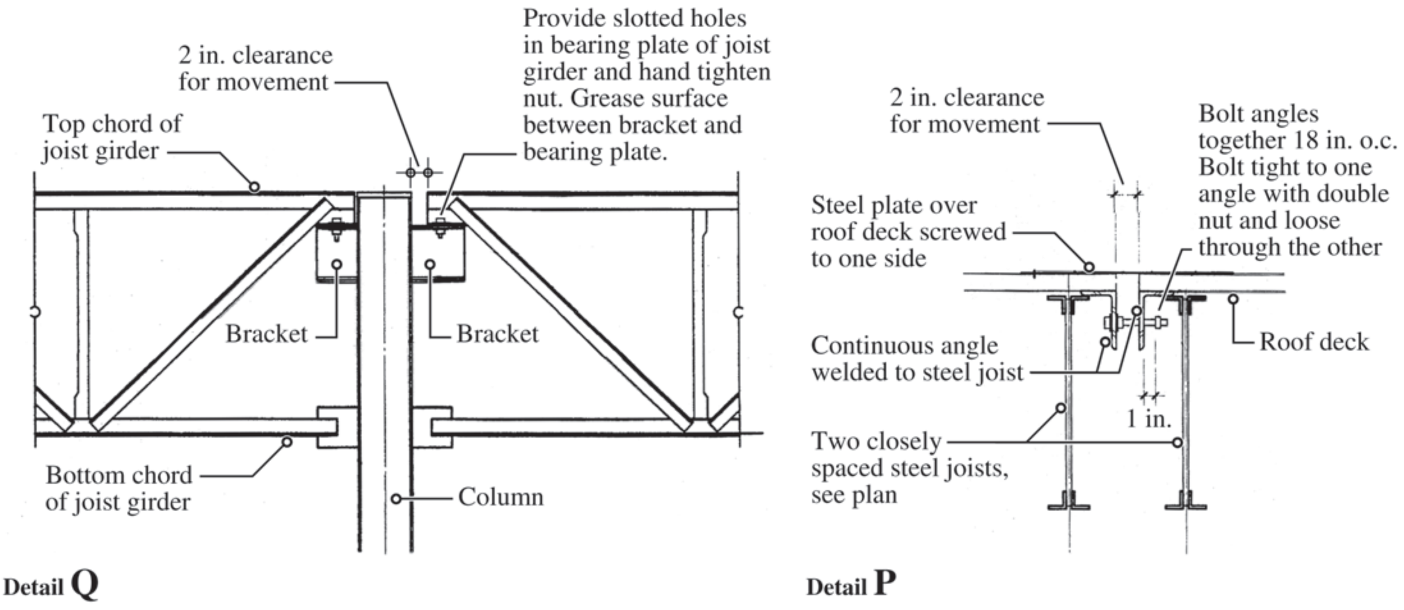
FIGURE 19.22 Details of the connection between W-shape beams and a column at a building separation joint using only one column (see Section 9.2 for an explanation of a building separation joint).

(*Continued*)

A Building Separation Joint in a Steel-Frame Building (*Continued*)


Exterior wall
Joist girder
Building separation joint
Two closely-spaced joists at building separation joints; see Detail P
Joist
Column
Q
P
Joist girder
Joist
Joist girder

(a) Roof framing plan


2 in. clearance for movement
Top chord of joist girder
Provide slotted holes in bearing plate of joist girder and hand tighten nut. Grease surface between bracket and bearing plate.
Bracket
Bracket
Bottom chord of joist girder
Column
Detail Q
2 in. clearance for movement
Bolt angles together 18 in. o.c. Bolt tight to one angle with double nut and loose through the other
Steel plate over roof deck screwed to one side
Roof deck
Continuous angle welded to steel joist
1 in.
Two closely spaced steel joists, see plan
Detail P

(b) Joist girder and column connection at building separation point

(c) Joists at building separation point

FIGURE 19.23 Details of a building separation joint in a single-story building with steel joists and joist girders (see Section 9.2 for an explanation of a building separation joint).

PRINCIPLES IN PRACTICE

Fundamentals of Frame Construction

Although frame construction in timber is much older, the real use of frame construction originated with the discovery of steel. A steel frame can be stabilized without braces. In a timber frame, on the other hand, some form of bracing is essential to obtain frame stability (see Principles in Practice at the end of Chapter 15). Frame stability without the use of braces is possible in steel because steel-frame members can be fused together at the joints through welding, giving continuity across the joints, that is, rigid connections. The only other material in which connection rigidity is obtained is cast-in-place concrete. Therefore, when we think of contemporary frame construction, we generally think either of *steel-frame construction* or *concrete frame construction*.

The fundamentals of frame construction described here, though focused on steel-frame construction, apply to concrete frame construction as well.

POST-AND-BEAM CONSTRUCTION

The earliest predecessor of the frame construction is the *post-and-beam* (also called *post-and-lintel*) *construction*. A post-and-beam assembly consists of columns (posts) and beams (lintels) with little or no connection between the posts and the beams. It was among the earliest construction systems devised by humankind, Figure 1. Ancient Egyptians, Greeks, and Romans used post-and-beam construction extensively to produce architectural masterpieces that stand until this day (see Figure 4.1).

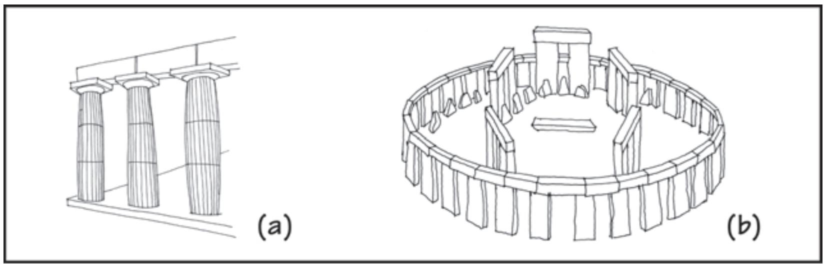


FIGURE 1 **(a)** A typical post-and-beam structure used by ancient Egyptians, Greeks, and Romans (Figure 4.1). **(b)** Stonehenge (United Kingdom, approximately 2500 to 1700 BC) is generally cited as the earliest surviving example of the post-and-beam structure.

A post-and-beam assembly works well for gravity loads. Under gravity loads, the beam is subjected to bending. Because there is no connection between the posts and the beam, the bending in the beam is not transferred to the posts, Figure 2. Consequently, the posts are under pure compression—no bending.

Under lateral loads (wind and earthquake), the post-and-beam assembly is theoretically unstable. When the lateral loads are within the plane of the post-and-beam assembly, the beam tends to slide over the column, and the column tends to overturn or slide along its base, Figure 3(a). If the lateral loads are perpendicular to the plane of the assembly, the entire assembly tends to overturn, Figure 3(b).

Early post-and-beam buildings used large, hefty stones. Stability of the building against overturning and sliding was achieved through large dead load of members and the friction between their surfaces.

A frame is similar to a post-and-beam assembly, except that the members of the frame (the columns and beams) are connected together. The connection between a column and a beam can be a *pin connection*, giving a pin-connected frame, or it can be a *rigid connection*, giving a rigid frame.

A pin-connected column-beam frame can be one of the following two types:

- Pin-connected cantilevered frame
- Pin-connected braced frame

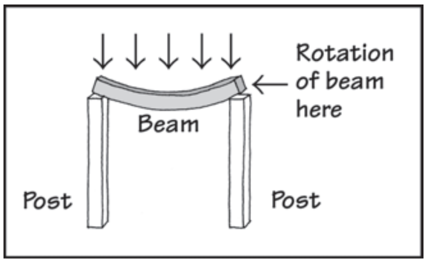


FIGURE 2 Under gravity loads, the beam in a post-and-beam structure is subjected to bending, which causes it to rotate at the joint. Because of the absence of a connection between the post and the beam, the rotation of the beam at the joint is not transferred to the post. The post is, therefore, subjected to compression only.

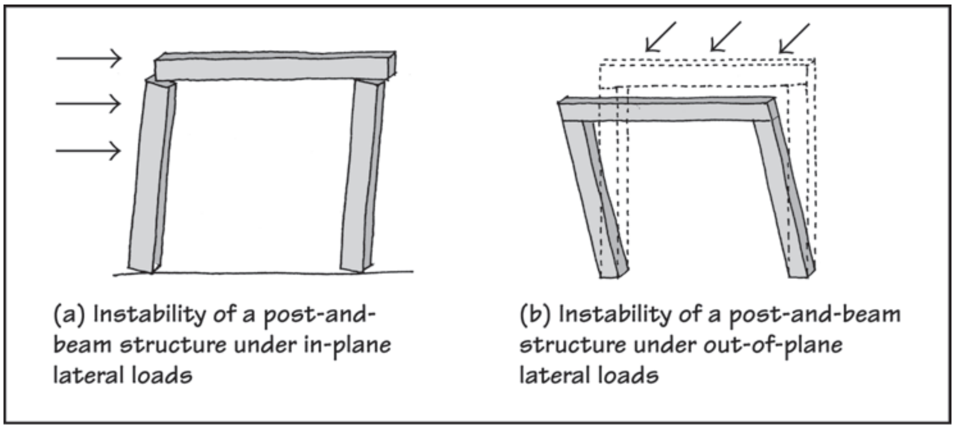

(a) Instability of a post-and-beam structure under in-plane lateral loads
(b) Instability of a post-and-beam structure under out-of-plane lateral loads

FIGURE 3 Under the action of both in-plane and out-of-plane lateral loads, a post-and-beam structure is unstable.

(Continued)

Fundamentals of Frame Construction *(Continued)*

PIN-CONNECTED CANTILEVERED FRAME

A pin connection is defined as a connection that allows the members to rotate at the connection independently of each other. In other words, the rotation of one member at the connection is not transferred to the other member. The simplest pin-connected frame consists of a single-bay frame (i.e., one beam and two columns) in which the beam is connected to each column through a single pin (a nail, screw, or bolt), Figure 4.

This connection allows the beam to bend and rotate under gravity loads without transferring the bending to the column. The connection, however, transfers the gravity load on the beam through shear created in the pin. A pin connection is, therefore, also referred to as a *shear connection*. Another term used for this connection is a *simple connection* (Section 19.3).

In practice, a shear (pin or simple) connection need not have lapped members, as shown in Figure 4. Additionally, welds or multiple nails, screws, or bolts may be used to achieve a pin connection. Thus, the connections between the studs and the top and bottom plates of a wood light frame, which are typically joined with two or three nails at each connection, behave as pin connections, Figure 5.

Similarly, the joints between wood truss members, connected together with nail plates (Section 14.4), are also considered pin connections. The same is true of the joints between the members of a steel joist or joist girder in which the members are welded together (Figures 18.20 to 18.22). Although such joints are not true (100%) pin connections, they provide adequate rotation of members at a joint to be considered pin connections.

In buildings, a joint detailed as a *true* pin connection is used for both structural and ornamental reasons, Figure 6. True pin connections are more common in civil engineering structures, such as waterway, highway, or railroad bridges. Details of commonly used shear connections between structural steel beams and columns were illustrated in Section 19.3.

In a conceptual line diagram of a pin-connected frame, a pin connection is represented by a hollow dot, and the columns and the beams are represented by single heavy lines, Figure 7. If the beam of a pin-connected frame is subjected to gravity loads, it will bend as shown in Figure 7(a). The bending of the beam (which causes the beam to rotate at the joint) is not passed on to the column. Therefore, the columns in a pin-connected frame come under pure compression, exactly as in a post-and-beam structure.

One way to ensure the stability of the frame in Figure 7 against lateral loads is to anchor the columns rigidly into the ground so that they are cantilevered from the ground like utility poles. Under the action of a lateral load, both columns will deflect horizontally, as shown in Figure 7(b)—a

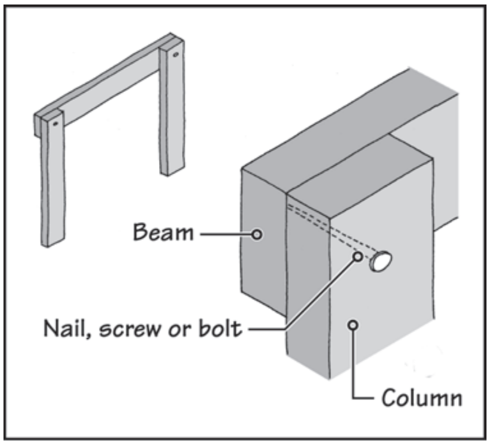


FIGURE 4 A single-bay, pin-connected frame in which the beam and column are connected together with a single nail, screw, or bolt. A pin connection is also referred to as a *shear connection* because the gravity load from the beam is transferred to the column, creating shear in the nail, screw, or bolt.

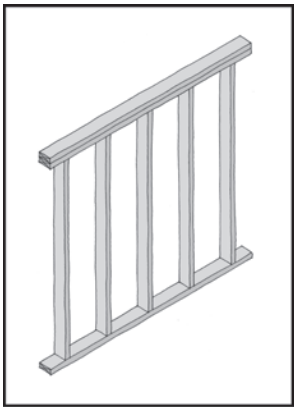


FIGURE 5 A connection between a stud and the top (or bottom) plate of a wood light frame, typically using two or three nails, is considered a pin connection.

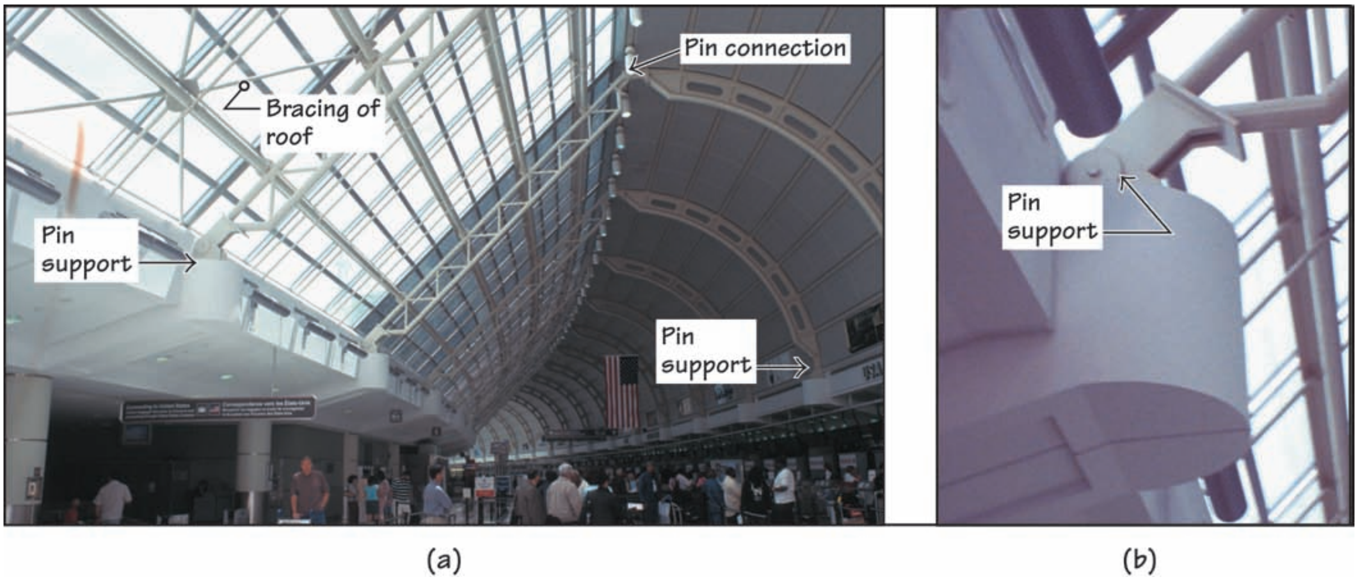


FIGURE 6 **(a)** A glass roof at Toronto Airport supported by three-pin frames. Each frame consists of two members, a linear trussed member and a curved hollow-web member. The members are joined at the top with a pin connection. **(b)** A pin connection has also been used to support each member at its support (base). All three pins in each frame have been detailed as true pins.

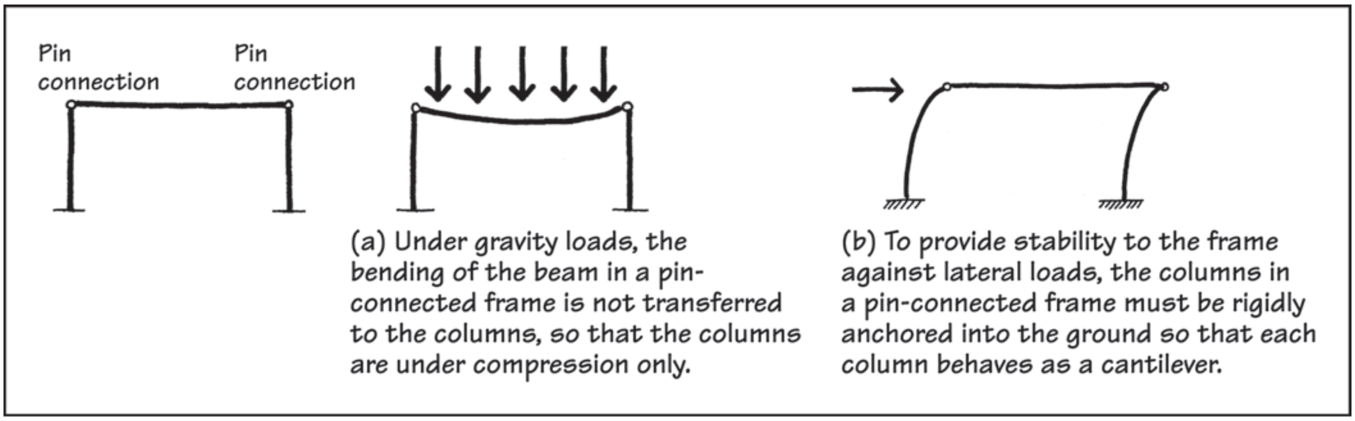

Pin connection
Pin connection
(a) Under gravity loads, the bending of the beam in a pin-connected frame is not transferred to the columns, so that the columns are under compression only.
(b) To provide stability to the frame against lateral loads, the columns in a pin-connected frame must be rigidly anchored into the ground so that each column behaves as a cantilever.

FIGURE 7 In a conceptual line diagram of a pin-connected frame, a pin is represented by a circular dot, and the frame members are represented by single heavy lines.

tendency called *racking*. Excessive racking of the cantilevered frame in Figure 7 is one of its major limitations. Racking can be reduced only by increasing the size and stiffness of columns—a solution that becomes increasingly inefficient as the column height increases.

Note that because of the pin connection between the beam and the columns, the bending in the columns of the cantilevered frame is not transferred to the beam. Thus, in transferring the lateral load from one column to the other, the beam in Figure 7 comes under compression.

Another limitation of the cantilevered frame in Figure 7 is the need for rigid column bases. The rigidity at the base of each column can be achieved by anchoring the column to the foundation, that is, by using a concrete footing. The footing must be heavy and sufficiently large so that the bending in the columns will not cause the footing to rotate.

A shallow, isolated column footing is generally not rigid enough to resist rotation, particularly if the footing is small and the soil is compressible. Such a footing simply rotates with the column, Figure 8(b), representing a *pinned column base*. A deep, large, and isolated column footing, Figure 8(c), or a mat footing in which several columns share a common footing (Section 12.1), is treated as a *rigid* (or *fixed*) *column base*.

NOTE

Racking of a Frame

The term *racking* refers to lateral deflection (angular deformation) of a frame under lateral loads and is an important design consideration. Building codes limit the amount of racking in buildings. Excessive racking causes occupant discomfort, damage to nonstructural components such as doors and windows, and fatigue in structural components, which may lead to structural failure over a period of time.

PIN-CONNECTED BRACED FRAME

In the conceptual line diagram, a pinned column base is represented in the same way as a pin connection, that is, by a circular dot. Thus, a single-bay, pin-connected frame in which the columns have pinned bases is a four-pin frame, Figure 9. Such a

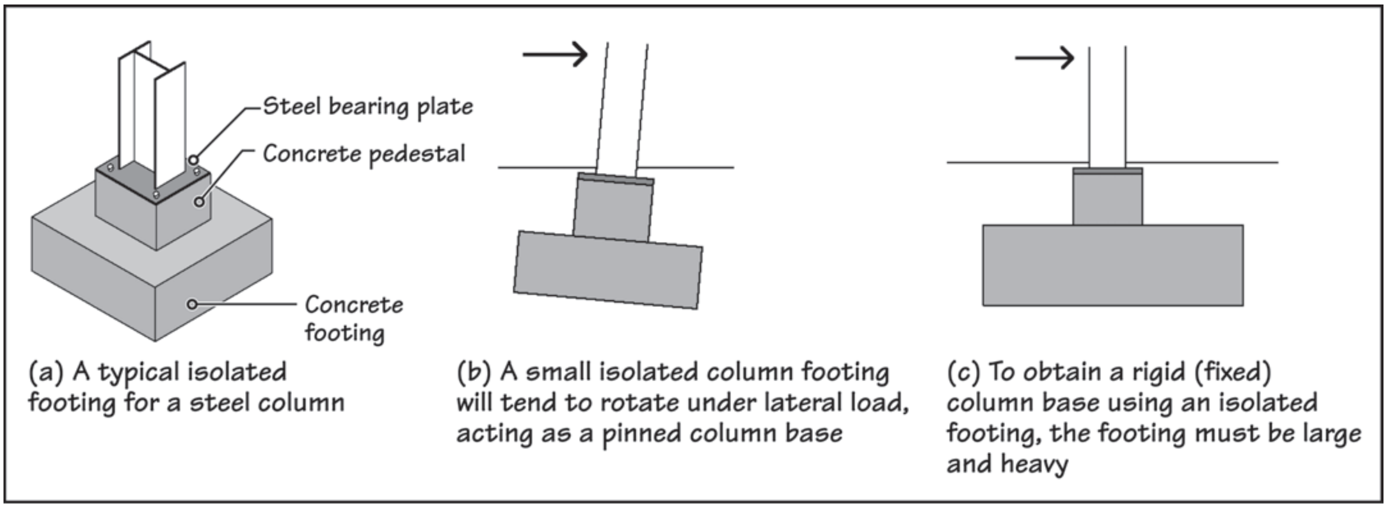

Steel bearing plate
Concrete pedestal
Concrete footing
(a) A typical isolated footing for a steel column
(b) A small isolated column footing will tend to rotate under lateral load, acting as a pinned column base
(c) To obtain a rigid (fixed) column base using an isolated footing, the footing must be large and heavy

FIGURE 8 **(a)** A typical isolated footing for a steel column. **(b)** A small column footing is believed to provide a pinned column base because it tends to rotate under the action of a lateral load. **(c)** To obtain cantilever behavior from a column with an isolated footing, the footing must be large and heavy.

(Continued)

PRINCIPLES IN PRACTICE

Fundamentals of Frame Construction *(Continued)*

frame is obviously unstable, as it will simply fold under lateral loads. A four-pin frame is also unstable under an unsymmetrical gravity load on the beam. In fact, a four-pin frame is not a structure, but a *mechanism*.

A four-pin frame can be stabilized, however, by bracing the frame in its own plane. The most efficient and most commonly used bracing system is a set of diagonal braces, also referred to as *X-bracing* or *cross bracing*, Figure 10. Under lateral loads, one diagonal brace is subjected to compression and the other to tension. The brace subjected to compression buckles under the load and becomes ineffective. Stability of the frame is, therefore, provided by the brace that is in tension. Because steel is strong in tension, X-bracing members need not be heavy. Therefore, X-bracing generally consists of steel rods, hollow pipes, plates, or angles. In high-rise structures, heavier sections such as wide-flange or hollow structural steel members are used.

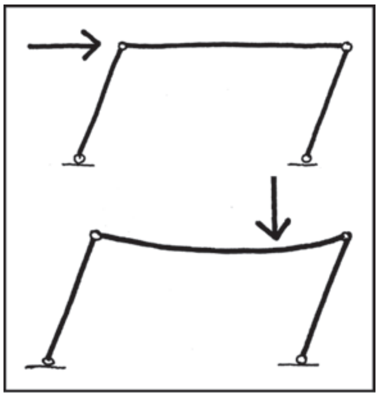


FIGURE 9 A four-pin frame is not a structure but a mechanism because it is unstable under both lateral loads and asymmetrical gravity loads.

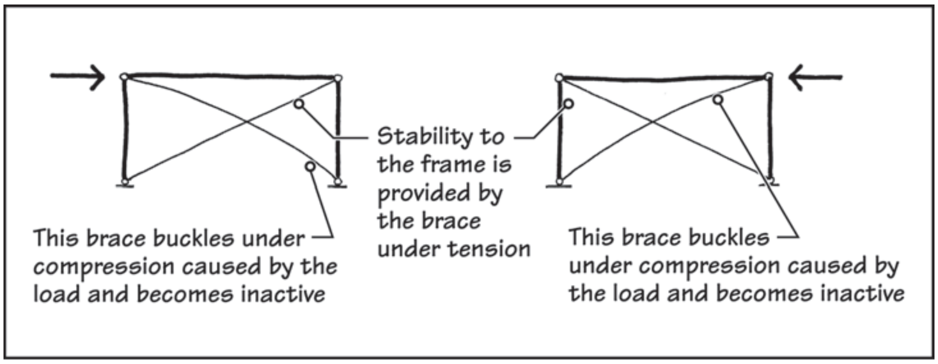

This brace buckles under compression caused by the load and becomes inactive
Stability to the frame is provided by the brace under tension
This brace buckles under compression caused by the load and becomes inactive

FIGURE 10 A four-pin frame can be stabilized by using X-bracing. Note that only one of the two X-braces is active under a lateral load.

Other bracing alternatives are the *K-brace* and the *eccentric K-brace*, Figure 11. K-bracing and eccentric K-bracing are generally used in multistory buildings, where substantial openings (doors or windows)

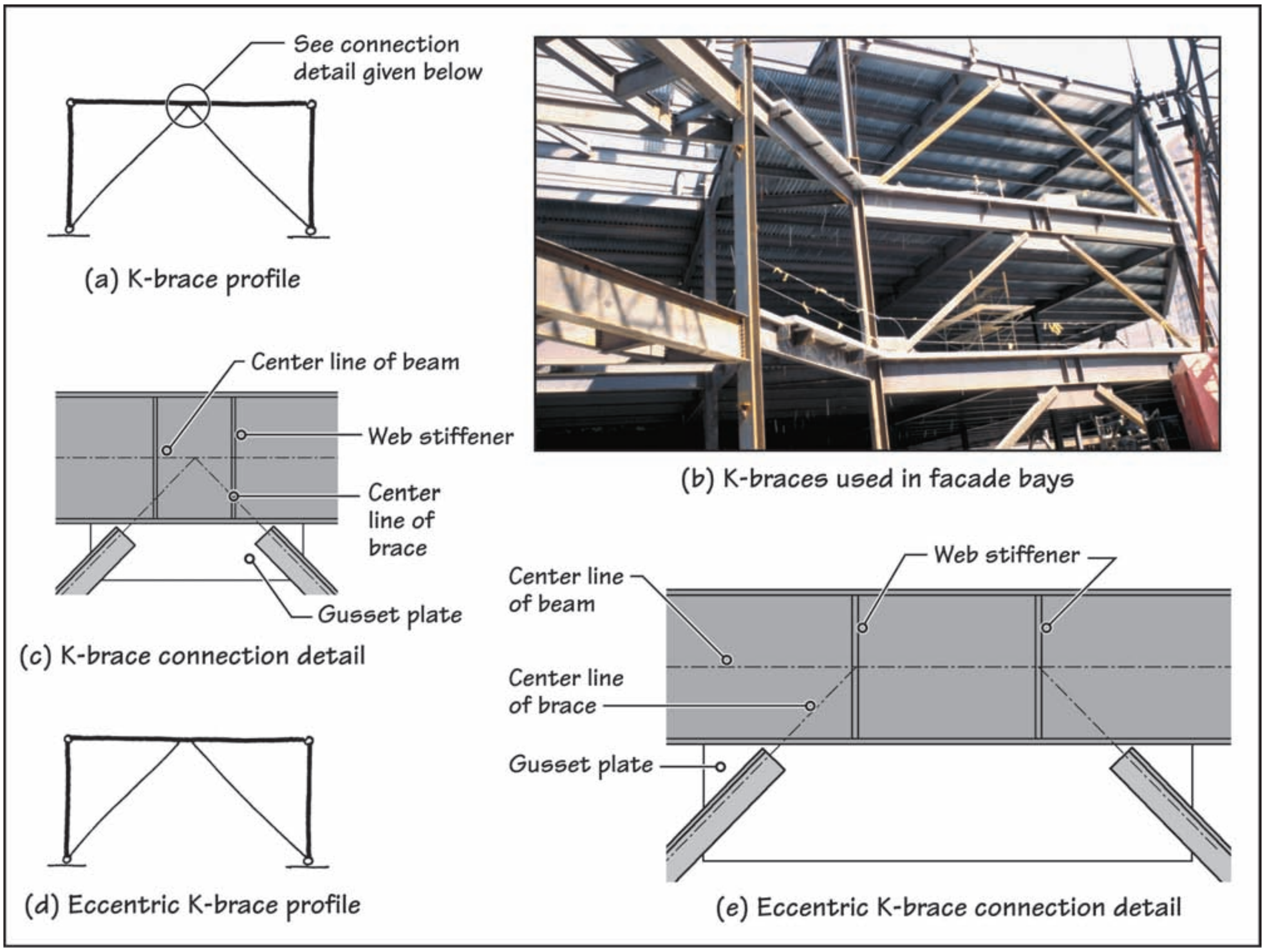

See connection detail given below
(a) K-brace profile
(b) K-braces used in facade bays
Center line of beam
Web stiffener
Center line of brace
Gusset plate
(c) K-brace connection detail
Center line of beam
Web stiffener
Center line of brace
Gusset plate
(d) Eccentric K-brace profile
(e) Eccentric K-brace connection detail

FIGURE 11 K-braces and eccentric K-braces.

are required in braced bays. The difference between the K-brace and the eccentric K-brace lies in their details. The braces in an eccentric K-brace do not meet at a point, leaving a small length of beam between the connections. An eccentric K-brace is generally recommended for use in seismic areas due to its ability to provide ductility of the frame.

Because a K-brace (or an eccentric K-brace) is connected to the center of the overlying beam, it must carry gravity loads on the beam, which halves the beam's span, reducing the beam size. Gravity load support implies that K-braces are heavier than X-braces. Thus, unlike X-braces, in which only one brace is active at a time, both K-braces are designed to resist tension as well as compression.

In low-rise buildings, one diagonal brace may be used, which must be heavy enough to resist compression as well as tension, Figure 12(a). A particularly interesting bracing alternative for a pin-connected frame is a *panel brace*, in which the entire space within the frame is filled with a panel, Figure 12(b). In concrete or steel structures, the panel brace consists of a masonry or concrete infill wall, referred to as an *infill brace* or *shear wall*.

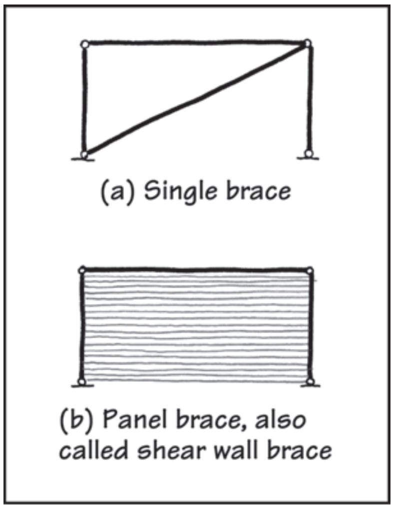


FIGURE 12 **(a)** If a single brace is used, it must be sufficiently heavy against buckling under compression. **(b)** Shear wall bracing.

RIGID FRAME

In a rigid frame the connections between the beam and the columns are rigid. Unlike a pin connection, a *rigid connection* retains a 90° angle between the connected members on deformation under the loads. Rigidity implies that the bending of one member is transferred through the joint to the other member. Therefore, a rigid connection is also called a *moment-resisting connection* or simply a *moment connection*.

Because both the beam and the columns bend together, all three members of a rigid frame function collectively in resisting a load. Consequently, when the beam of a rigid frame is subjected to gravity loads, its deformation is smaller than that of the beam in a pin-connected frame. In the conceptual line diagram, a moment connection is represented by a small diagonal thickening of the joint, as shown in Figure 13.

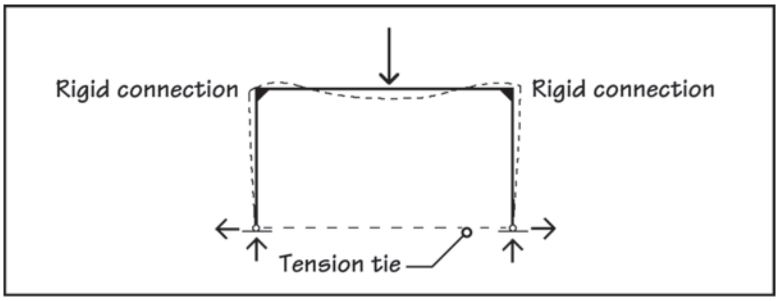


FIGURE 13 Unlike a pin connection, a rigid connection retains its 90° angle between the connected members on deformation. Consequently, a rigid frame resists gravity loads by creating bending in all three frame members. Because bending is structurally inefficient, a rigid frame is generally less economical than a comparable braced frame.

Note that a rigid frame under gravity loads experiences an outward thrust in column bases similar to that of an arch.

In a single-line diagram of the frame, a rigid connection is denoted by diagonal thickening of the joint.

RIGID FRAME VERSUS BRACED FRAME

A rigid frame does not require bracing for lateral stability, providing an unobstructed space. However, a rigid connection is more difficult to make than a shear connection. In a wood rigid frame, joint rigidity may be obtained by securely fastening a plywood or OSB gusset plate on both sides of the joint, Figure 14. Compare this with simply nailing the members together to obtain a pin connection.

As illustrated later, the difference between a rigid connection and a shear connection is even more pronounced in a steel-frame structure. Simplicity of connections is one reason why braced steel frames are preferred over rigid steel frames.

Braced frames are generally less expensive and allow faster erection. Rigid-frame structures are used only where braced frames are architecturally unacceptable because of the obstruction caused by the braces. Some of the other advantages of a braced frame over a rigid frame are as follows:

- The columns in a rigid frame are subjected to bending under lateral loads (Figure 13). In a braced frame, the columns are subjected to axial stresses only. Because bending is an inefficient structural action, the columns in a rigid frame are heavier than the columns in a braced frame. This difference becomes progressively more pronounced as the height of the structure increases.

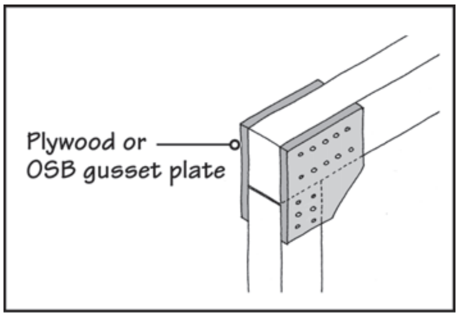
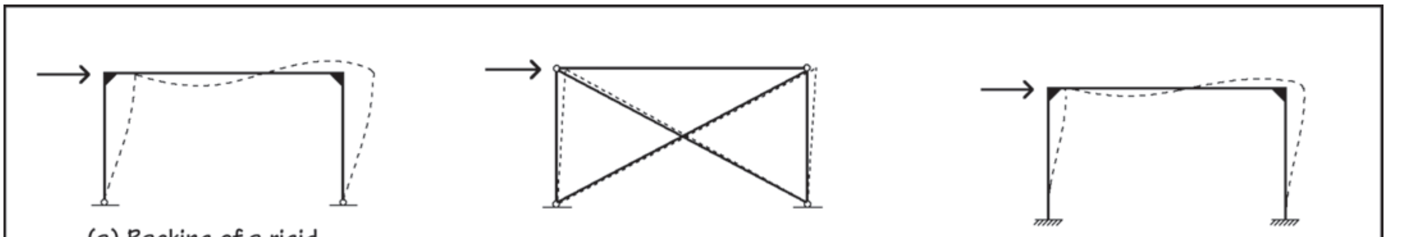


FIGURE 14 A rigid connection between two wood frame members can be obtained by nailing a plywood or OSB gusset plate on both sides of the joint. A rigid connection between two steel members is more complex (see Figure 19.11).

(Continued)

PRINCIPLES IN PRACTICE

Fundamentals of Frame Construction *(Continued)*



(a) Racking of a rigid frame with pinned bases under lateral loads.

(b) Racking of a braced frame under lateral loads is due to the elongation of the brace, and shortening and settlement of column footing under compression.

The racking of a braced frame is much less than that of a rigid frame even when the rigid frame is supported on fixed column bases. A braced frame is, therefore, much stiffer than a corresponding rigid frame.

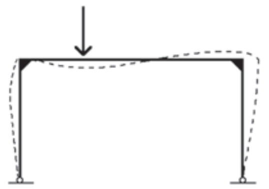
A K-braced frame is stiffer than a corresponding X-braced frame because of its shorter diagonals.

(c) Racking of a rigid frame with fixed bases under lateral loads is smaller than that of a rigid frame with pinned bases.

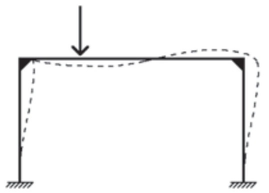
FIGURE 15 Comparison of the racking of a rigid frame and a braced frame.

- The racking of a rigid frame is larger than that of a comparable braced frame, Figures 15(a) and (b). In fact the term *rigid* is a misnomer because a braced frame is much stiffer than a corresponding rigid frame. The racking of a rigid frame can be decreased somewhat by using fixed (rigid) column bases, but the increase in stiffness so obtained does not match the inherent stiffness of a braced frame, Figure 15(c). Racking of a rigid frame also occurs under asymmetrical gravity loads, Figure 16.
- Another limitation of a rigid frame is its arching action, which makes the columns spread out under gravity loads, requiring a heavier footing or a tie that connects the column footings (Figure 13).

Because of its several limitations, a rigid-frame solution for a building that is more than six or seven floors in height becomes too uneconomical to justify its use.



(a) Rigid frame with pinned bases



(b) Rigid frame with fixed bases

FIGURE 16 Racking of the frame is produced even under asymmetrical gravity loads, which is more pronounced in a rigid frame than in a braced frame.

MULTIBAY SINGLE-STORY FRAMES

The fundamentals discussed with respect to single-bay frames also apply to multibay frames. However, it is not necessary to brace every bay of a multibay frame. Sufficient frame stiffness can be achieved by bracing a few selected bays in a single-story, multibay frame building. For example, in a four-bay, single-story frame, either two end bays or two central bays may be braced, Figures 17(a) and (b). Where lateral loads are small, bracing of only one bay may be sufficient, Figure 17(c).

The three-dimensional nature of the building requires that the frames in both principal directions be braced, Figure 18(a). As far as possible, braced bays should be symmetrically located in the building. Asymmetrical locations of braced bays are structurally inefficient but may be used where architectural considerations dictate their use. A combination of a rigid frame and a braced frame may also be used. In a common braced - and rigid-frame combination, the rigid frame is used along one principal direction of the building and the braced frame is used along the other direction, Figure 18(b).

Just as every bay of a multibay braced-frame structure need not be braced, every bay of a multibay rigid frame need not be a rigid frame. Sufficient rigidity may be obtained by using rigid column-beam connections for a few selected bays and leaving the others as pin connections, Figures 19(a) and (b).

STIFFNESS OF HORIZONTAL DIAPHRAGMS (FLOORS AND ROOF)

Resistance to lateral loads in a building requires that various components of the building function interactively. This implies that the horizontal diaphragms (floors and roof) of the building should be sufficiently stiff so that they can transfer lateral loads from the vertical elements on one face of the building to the vertical elements on other faces.

Generally, reinforced concrete floors, concrete-filled steel deck floors, and insulation-topped steel roof decks have sufficient stiffness for the purpose (referred to as providing *diaphragm action*). Where diaphragm action is not available, bracing of roofs may be needed (see Figure 18). (See also Figure 6, where the large glazed roof is braced by diagonal braces.)

MULTISTORY STEEL FRAMES

Although the principles of framing a multistory building are similar to those of framing a multibay, single-story building, a much larger number of solutions exist as the building height increases. Complete coverage of the framing solutions for high-rise buildings is outside the scope of this text. The coverage provided here is limited to buildings up to 30 to 40 stories in height.

For a low-rise multistory building, a steel rigid frame may be used. Note once again that a rigid-frame solution becomes progressively uneconomical with increasing building height due to the inordinate increase in column and beam sizes. However, because of the absence of braced bays, it provides greater adaptability in organizing the interior spaces and exterior elevations. A typical steel rigid-frame structure is shown in Figure 20.

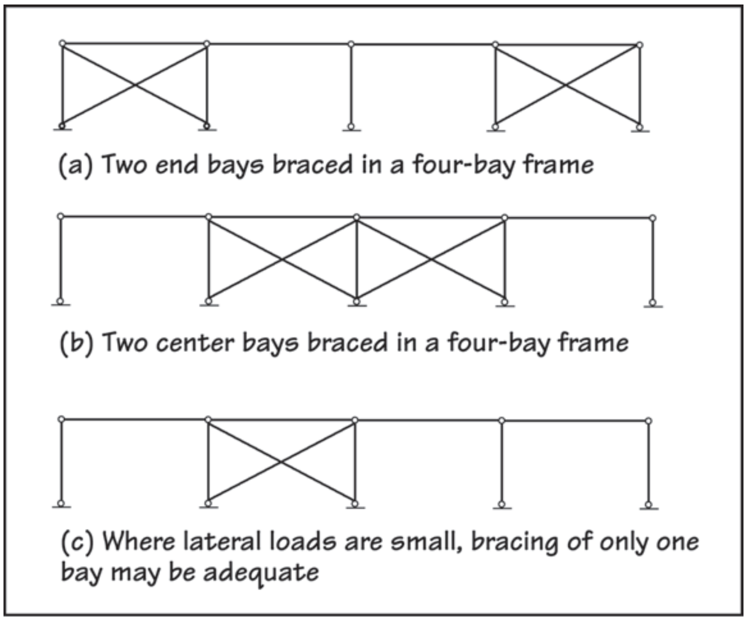

(a) Two end bays braced in a four-bay frame
(b) Two center bays braced in a four-bay frame
(c) Where lateral loads are small, bracing of only one bay may be adequate

FIGURE 17 Some of the ways of bracing a four-bay, single-story frame.

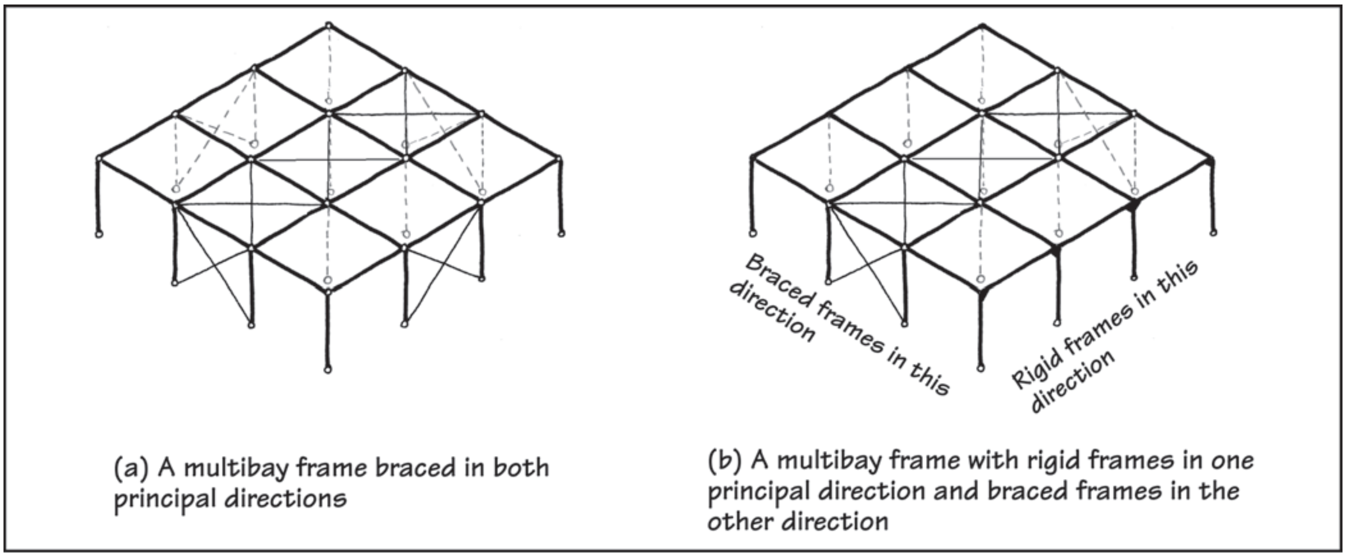

Braced frames in this direction
Rigid frames in this direction
(a) A multibay frame braced in both principal directions
(b) A multibay frame with rigid frames in one principal direction and braced frames in the other direction

FIGURE 18 **(a)** Braced frames in both principal directions. **(b)** Braced frames in one direction and rigid frames in the other direction.

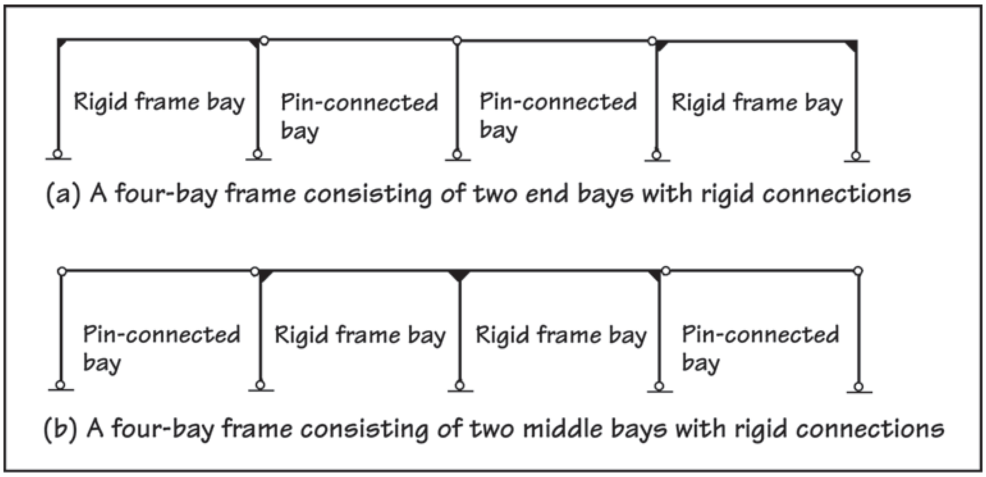

Rigid frame bay
Pin-connected bay
Pin-connected bay
Rigid frame bay
(a) A four-bay frame consisting of two end bays with rigid connections
Pin-connected bay
Rigid frame bay
Rigid frame bay
Pin-connected bay
(b) A four-bay frame consisting of two middle bays with rigid connections

FIGURE 19 It is possible to obtain sufficient rigidity by using rigid connections in a few bays of a multibay frame.

(Continued)

Fundamentals of Frame Construction *(Continued)*

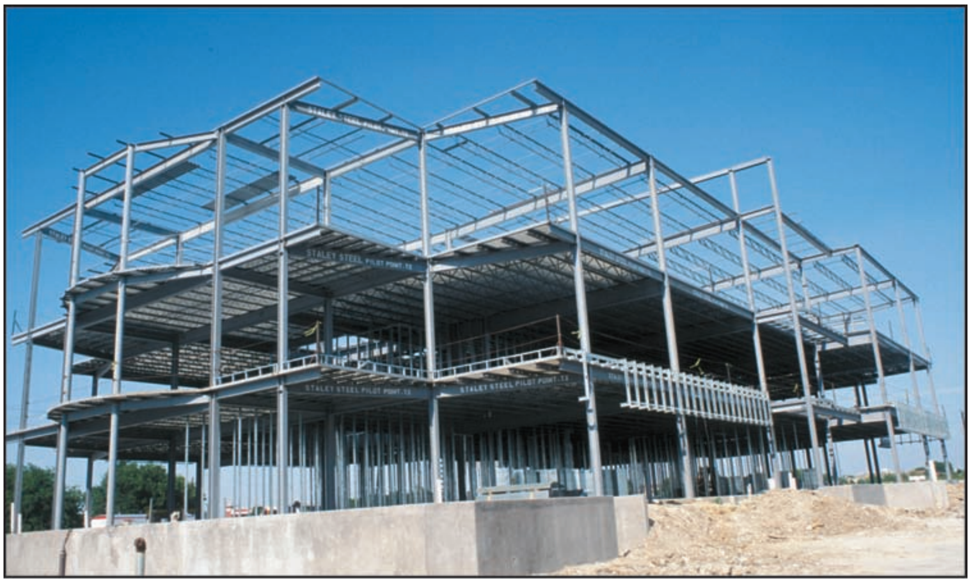


FIGURE 20 A typical steel rigid-frame building. Observe the absence of braced bays, which gives greater freedom in organizing the interior spaces and building's facade.

A braced-frame structure is more commonly used for both low-rise and high-rise buildings. The bracing may be incorporated in the exterior bays, where it is generally most efficient. In a large building, a few interior bays may also need to be braced, Figure 21. In a braced steel-frame building, all column-beam connections are simple connections.

TALL BUILDINGS IN STEEL

The ideal locations for interior bracing are around staircase shafts, elevator shafts, restrooms, and so on, because such spaces do not require large openings. A frequently used bracing system for tall buildings (up to 30 or 40 stories) is to brace only a few interior bays in the center of the building, giving a rigid central *shear core*, Figure 22. By providing the shear core, all the lateral loads are resisted by the core. Therefore, the columns, which are not part of the core (e.g., perimeter columns), do not resist any lateral loads. They are designed to resist gravity loads only. Additionally, all column-beam connections are simple connections.

The core is used to enclose functions such as stairs, elevators, restrooms, and HVAC shafts. For an office building, the core may occupy as much as one-third of the total floor area of the building at each floor. The core also permits the perimeter of the building to be fully glazed.

An alternative to a braced shear core is to use a reinforced concrete shear core, Figures 23 and 24. The reinforced concrete core provides rigidity to the building by behaving as a tube. The tube may have perforations to accommodate doors

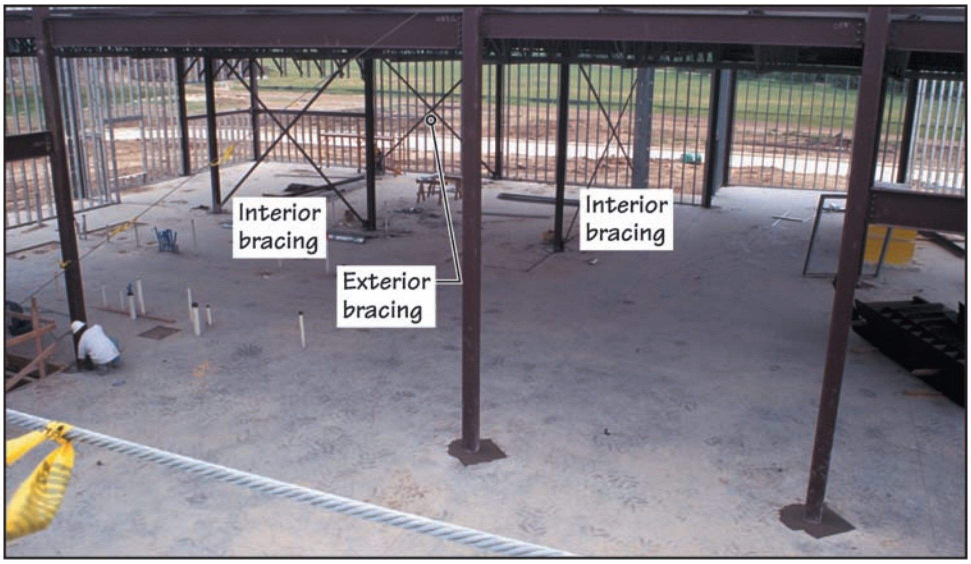


FIGURE 21 A typical braced-frame building. Observe the provision of braced bays in the interior as well as the exterior of the building.

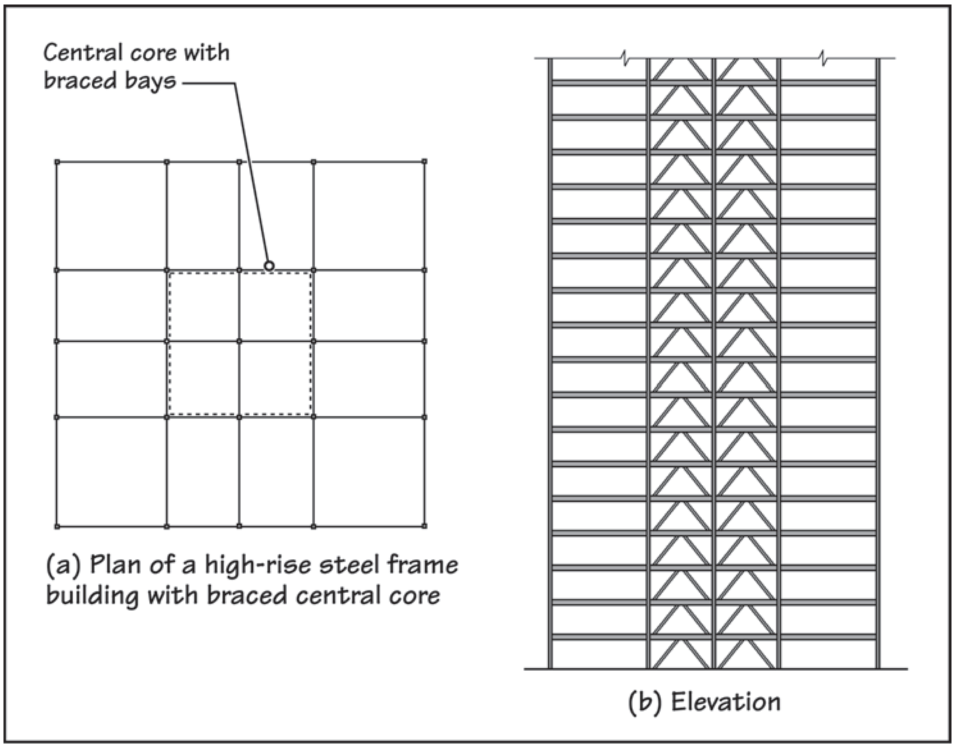

Central core with
braced bays
(a) Plan of a high-rise steel frame
building with braced central core
(b) Elevation

FIGURE 22 Plan and elevation of a high-rise steel-frame building with a braced steel-frame shear core.

and other openings as long as the perforations are not too large. A reinforced concrete core has an advantage over a braced steel-frame core because of its inherent high fire resistance, which is generally mandated for stair and elevator shafts.

A particularly elegant building consisting of a reinforced concrete core is the 12-story office building shown in Figure 25. In this building there are no perimeter columns, and the floors, consisting of steel wide-flange beams, have been suspended from the top of the core with steel cables.

In a high-rise building, which is much longer in one direction than in the other direction, a combination of a shear core and braced end shear walls is often used, Figure 26.

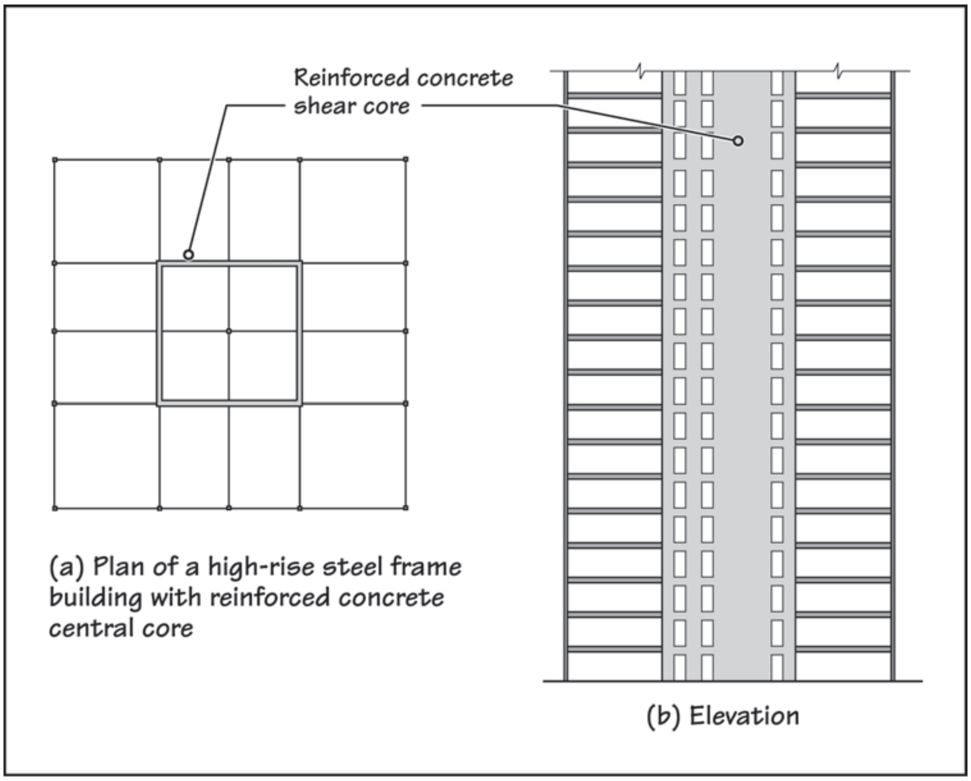

Reinforced concrete
shear core
(a) Plan of a high-rise steel frame
building with reinforced concrete
central core
(b) Elevation

FIGURE 23 Plan and elevation of a high-rise steel-frame building with a reinforced concrete shear core.

(Continued)

Fundamentals of Frame Construction *(Continued)*

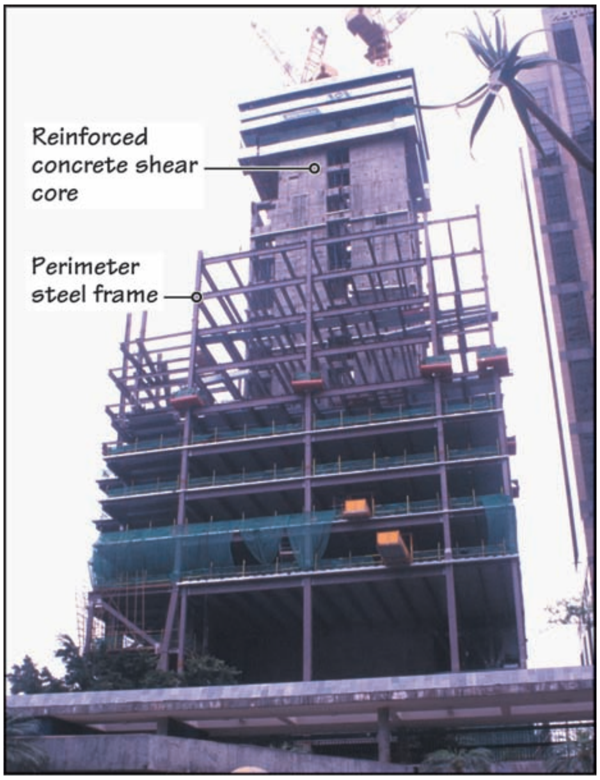

Reinforced concrete shear core
Perimeter steel frame

FIGURE 24 A steel-frame building with a reinforced concrete central core under construction in Hong Kong.

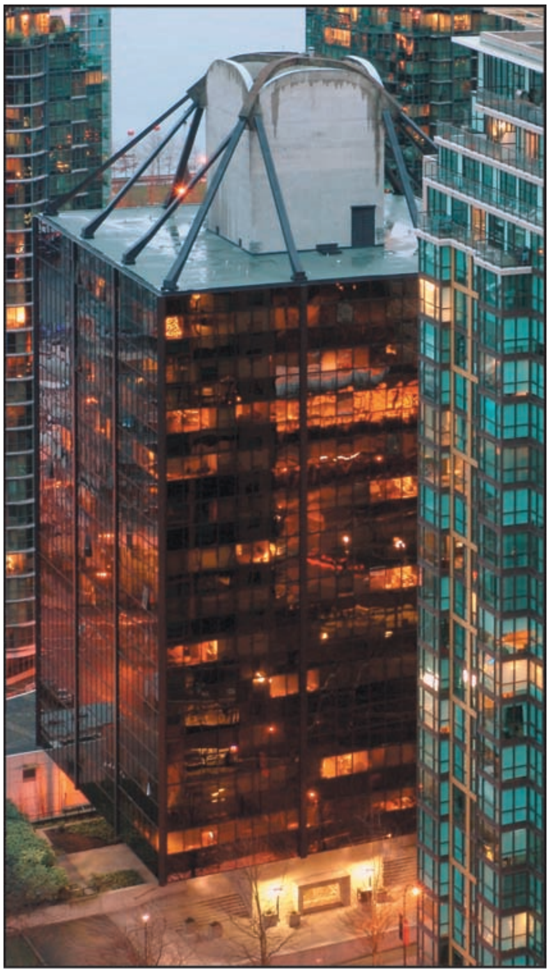


FIGURE 25 The 12-story West Coast Transmission Company Building, Vancouver, Canada, consisting of a reinforced concrete shear core. Note that there are no columns in the building, and the only support system is a reinforced concrete central core. The absence of columns gives a large, column-free space at the ground. The floors are framed out of steel wide-flange beams and are suspended at the perimeter from the core with steel cables. Similar buildings (with floors suspended from a concrete or steel-framed central core) have been constructed in several places [Ref. 19.1]. (Photo by Alexander Ulyanov/Emporis)

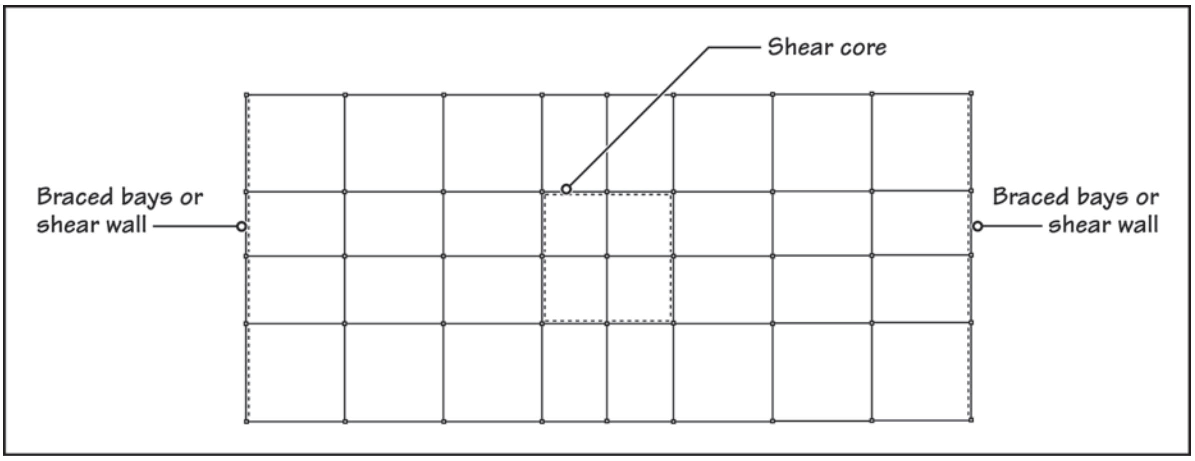

Shear core
Braced bays or shear wall
Braced bays or shear wall

FIGURE 26 A commonly used method of framing a tall building that is much longer in one direction than the other is to use a central core and two end shear walls (or braced bays).

PRINCIPLES IN PRACTICE

LONG-SPAN STEEL BUILDINGS

Just as steel is the only structural material available for very tall buildings (skyscrapers), it is also the only material suitable for long-span structures (spans greater than 100 ft). Long-span structures are typically required for sports facilities, convention centers, atriums, and other assembly spaces.

For spans of up to about 200 ft, the use of steel joists provides an economical solution. For longer spans, two-way trusses, two-way W-shape grid structures, and steel space frames are often used, Figures 27 and 28.

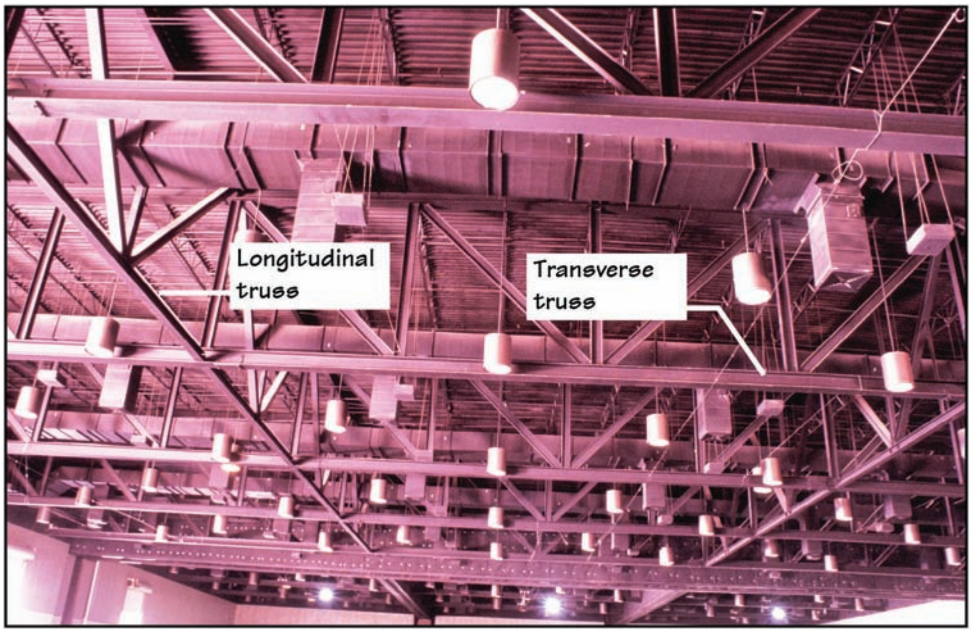


FIGURE 27 The use of two-way steel trusses in the main hall of the Convention Center, Arlington, Texas (truss spans are 300 ft × 400 ft).

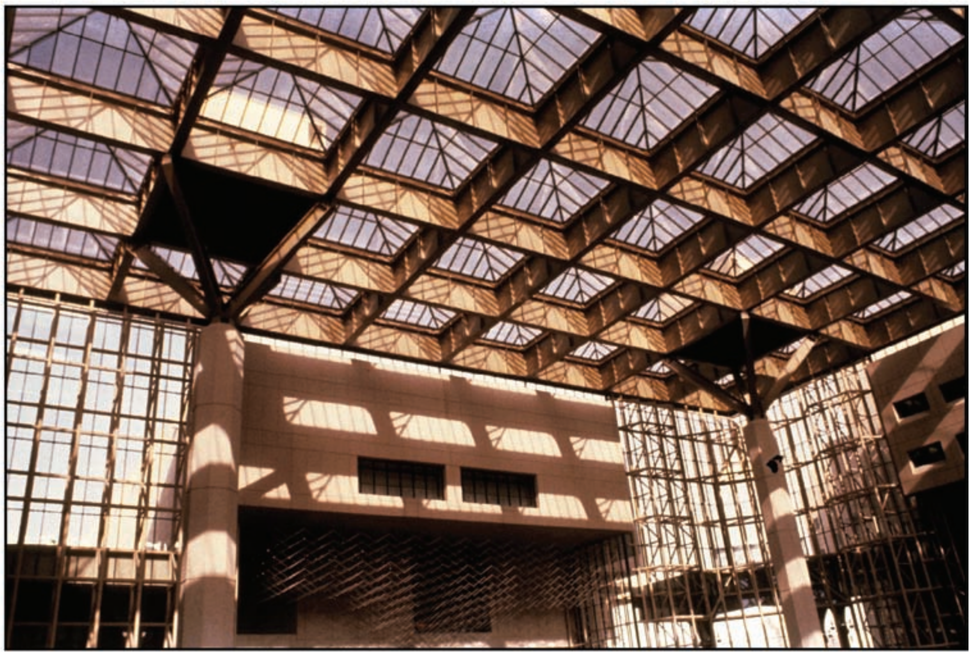


FIGURE 28 The roof of a large atrium space consisting of two-way grid of W-shape beams, King Saud University, Riyadh, Saudi Arabia.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

24. A braced-frame steel structure is generally more economical than a comparable rigid-frame structure.
a. True **b.** False

25. The difference between diagonal bracing and K-bracing between steel columns is that
a. K-bracing provides less spatial interruption than diagonal bracing.
b. K-bracing members are heavier than diagonal bracing members.
c. K-bracing members also carry some gravity loads, while diagonal framing members do not.
d. all of the above.
e. none of the above.

26. Eccentric K-bracing is generally recommended for use
a. because it is more economical than other forms of bracing.
b. because it increases frame stability more than other forms of bracing.
c. in hurricane-prone regions.
d. in seismic regions.
e. all of the above.

27. The term *racking* refers to the effect produced on the structure mainly by
a. dead loads. **b.** floor live loads.
c. roof live load. **d.** lateral loads.
e. none of the above.

28. A steel-frame building may consist of either a rigid frame or a braced frame. A combination of the two systems (braced- and rigid-frame systems) cannot be used in the same building.
a. True **b.** False

29. Which of the two—a rigid frame or a braced frame—provides greater structural stiffness, that is, greater lateral stability?
a. Rigid frame **b.** Braced frame

30. In a braced-frame steel structure, the braced bays
a. should be provided only on the exterior facade of the building.
b. should be provided only in the interior of the building.
c. should be provided on both the exterior facade and the interior of the building.
d. may be provided on the exterior facade or the interior of the building.
e. may be provided on the exterior facade, the interior of the building, or both.

31. A multistory steel-frame structure must be provided with a central shear core.
a. True **b.** False

32. The central shear core in a steel-frame building
a. should consist of reinforced concrete walls in both directions of the building.
b. should consist of steel-braced frames along both directions of the building.
c. either (a) or (b).
d. should consist of reinforced concrete walls in one direction of the building and steel-braced frames in the other direction.

REVIEW QUESTIONS

1. Explain what the term *framing plan* means. What information does a framing plan include?
2. In a typical structural steel floor or roof framing, there are three types of elements, called *primary*, *secondary*, and *tertiary elements*. Explain what these are and what material(s) they consist of.
3. Explain the pros and cons of welding versus bolting in steel structures.
4. With the help of sketches and notes, explain the difference between a simple connection and a rigid connection between a wide-flange column and a wide-flange beam.
5. With the help of sketches and notes, explain the connection of a column of an upper floor with that of a lower floor.
6. Explain the roles of the general contractor, fabricator, and erector of a structural steel building.
7. Using sketches and notes, explain how the joists and joist girders are stabilized against overturning.

CHAPTER 20

Cold-Formed Steel Construction

CHAPTER OUTLINE

20.1 SPECIFICATIONS FOR CFS MEMBERS

20.2 CROSS-SECTIONAL PROFILES OF CFS MEMBERS

20.3 STRUCTURAL AND NONSTRUCTURAL CFS MEMBERS

20.4 EQUIVALENT (EQ) STUDS AND TRACKS

20.5 CFS IN INTERIOR DRYWALL PARTITIONS

20.6 INTERIOR DRYWALL PARTITIONS—DEFLECTION OF OVERHEAD STRUCTURE

20.7 EXTERIOR NON-LOAD-BEARING (CURTAIN) WALLS

20.8 CFS FRAMING IN LOAD-BEARING APPLICATIONS

20.9 CFS BUILDINGS AS TYPE V(B) CONSTRUCTION

20.10 THERMAL PERFORMANCE OF CFS WALL ASSEMBLIES

20.11 MAKING OF CFS MEMBERS

As stated in Section 18.3 and as illustrated at the end of this chapter, cold-formed steel (CFS) members are made by bending steel sheets into various cross-sectional profiles at room temperature. These profiles are used in many applications; the more important ones are as follows:

1. CFS in non-load-bearing applications
   - CFS framing for interior drywall (gypsum board) partitions and ceilings
   - CFS framing in walls used as backup for exterior cladding
2. CFS in structural framing of load-bearing wall buildings

The other important uses of CFS are in (ribbed) floor and roof decks, commonly used in buildings framed with structural steel and cold-formed steel. Steel decks have been covered in Chapter 18. This chapter deals with the use of CFS framing in items 1 and 2 above. Note that CFS is also referred to as *light-gauge steel* (LGS) in some literature.

NON-LOAD-BEARING WALLS—INTERIOR PARTITIONS AND WALLS FOR EXTERIOR CLADDING

A widespread use of CFS occurs in the framing of interior drywall (gypsum board) partitions in buildings of Type I and Type II construction. For these buildings, the building codes mandate the use of noncombustible materials in structural frame (columns and beams), interior and exterior walls (see Chapter 7 for the definition of Type I and Type II construction).

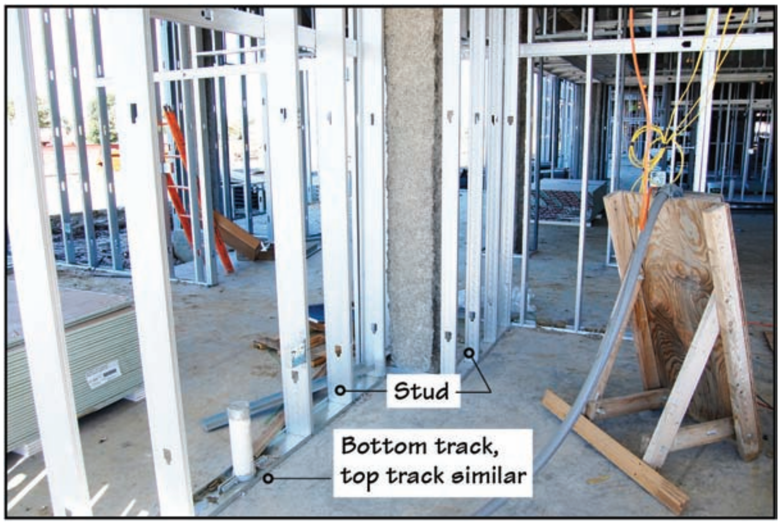

Stud
Bottom track,
top track similar

FIGURE 20.1 CFS members used in the framing of interior partitions. The framing members shown here will be covered with drywall (gypsum board).

Being noncombustible, lightweight and relatively easy to assemble, CFS is the material of choice for the construction of interior partitions in these buildings, Figure 20.1. According to one of the largest manufacturers of CFS members, approximately 60% of all CFS is used for interior drywall partitions [Ref. 20.1].

CFS is also used extensively in buildings of Type I and Type II construction for the framing of exterior walls that function as backup for cladding—brick veneer, stucco, EIFS, etc., Figure 20.2. In both applications (interior partitions and exterior walls), CFS members are non-load-bearing, that is, the primary load demand on them is to resist lateral loads. The gravity load on them is small, which is mainly due to their self load and the cover materials, such as interior gypsum board, and exterior sheathing.

From the margin note in Section 15.6, the reader would recall that a *load-bearing element* is defined as one that resists all loads on the element—lateral loads plus the gravity loads. A *non-load-bearing element* is one that would resist lateral loads only; the gravity load it must resist is its self load.

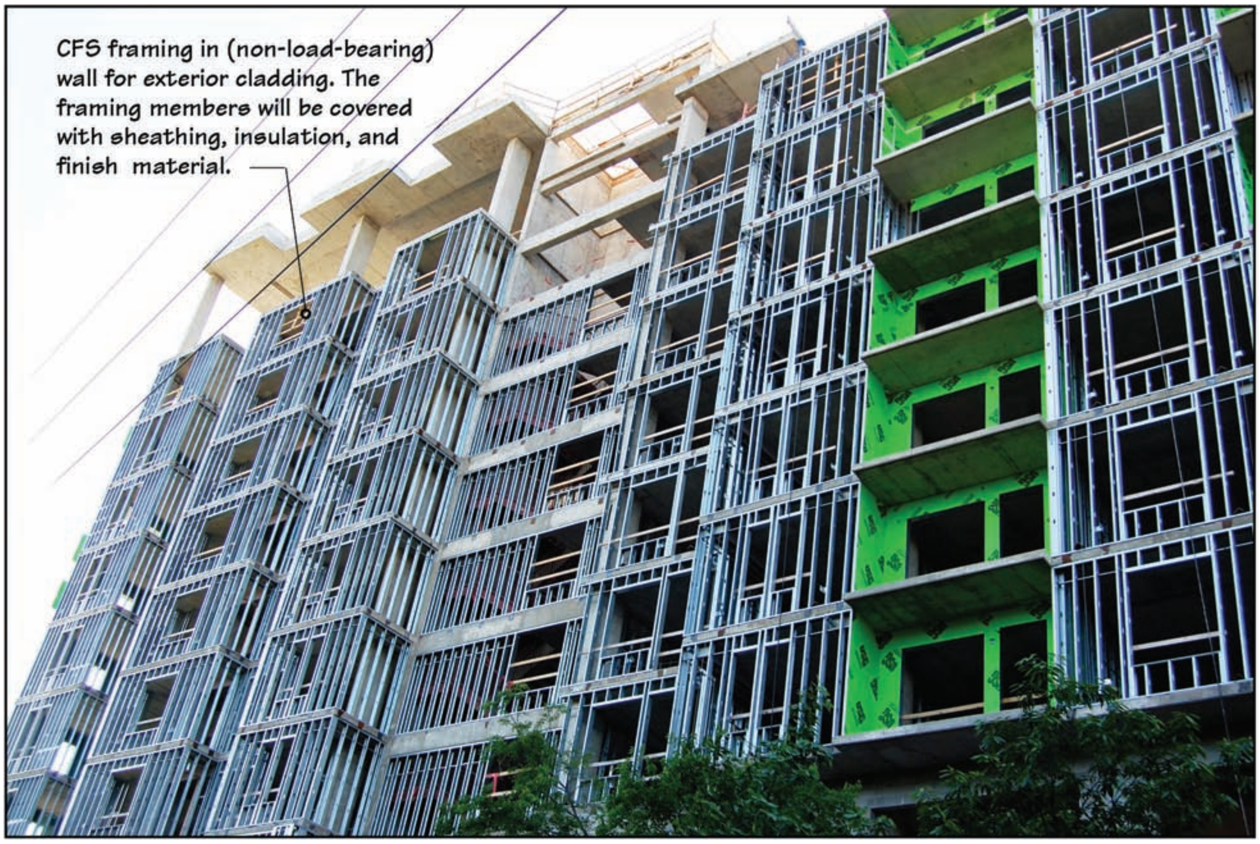

CFS framing in (non-load-bearing) wall for exterior cladding. The framing members will be covered with sheathing, insulation, and finish material.

FIGURE 20.2 CFS framing members in this exterior wall function as backup for exterior cladding. The green-color board, shown here, is the exterior (glass-matt-faced gypsum) sheathing, which will cover the entire CFS framing. Insulation and exterior finish material will be applied to sheathing.

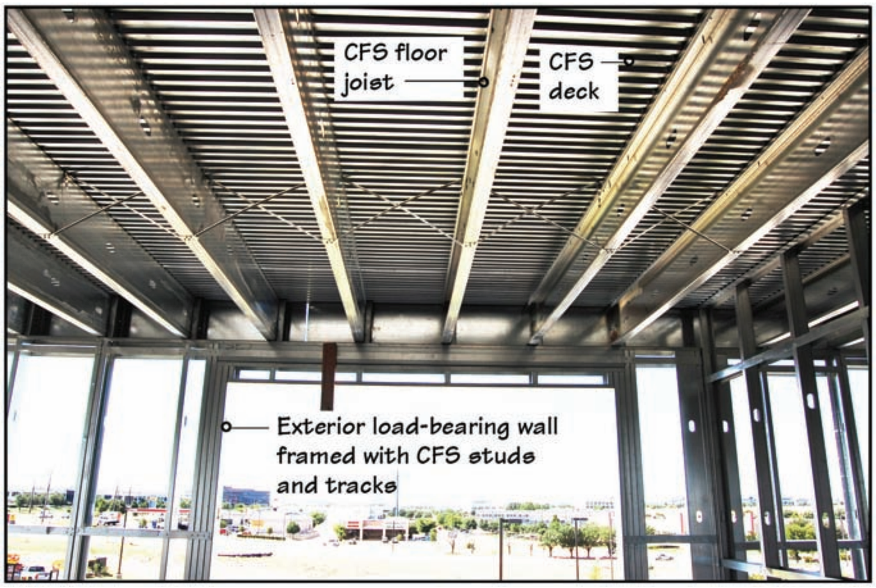


FIGURE 20.3 Walls framed with CFS members support the floor of this building, which is framed with CFS joists. The joists support the CFS deck above.

CFS in Load-Bearing Wall Buildings

While the use of CFS in non-load-bearing walls has existed for a long time, its use in the load-bearing elements is more recent. In this application, CFS is used in all load-bearing and non-load-bearing assemblies of the building—walls, floors, and roofs, Figure 20.3. This construction is similar to that of wood light-frame construction (discussed in Chapter 15).

One region that has seen an increasing use of CFS in load-bearing wall applications is the western United States, where CFS's higher strength, greater ductility, and lower dead load gives it an advantage over the wood frame in resisting seismic forces. Other areas of growth are warm, humid areas that are infested with termites and/or susceptible to mold growth. Durability against termites is the primary reason for the popularity of CFS in the structural framing of homes in Hawaii, Florida, Georgia, and parts of Texas, which (in the absence of termites) would have been framed in wood.

The first few sections of this chapter deal with non-load-bearing CFS wall construction, and the later sections cover the construction of load-bearing wall buildings.

20.1 SPECIFICATIONS FOR CFS MEMBERS

The most important specification items for CFS members are as follows:

- Corrosion protection
- Sheet thickness
- Sheet strength

Corrosion Protection for CFS Members

Because they are made from thin sheets of steel, CFS members must be protected from corrosion. Except for steel roof decks, which may be paint finished, CFS members are generally hot-dip galvanized. In this process, a thin coating of zinc is bonded to steel sheet. The thickness of zinc coating (the degree of corrosion protection) depends on CFS members' use (interior partitions, exterior wall cladding, or load-bearing assemblies). G40 and G60 are commonly used coatings. In more corrosive environments, such as coastal areas, G90 may be specified.

As stated in Section 18.7, G60 means that that the member has been hot-dip galvanized with a total weight of zinc coating on all its surfaces equal to 0.60 oz per sq ft. Similarly, G40 has 0.40 oz of zinc per sq ft.

American Iron and Steel Institute (AISI) recognizes galv-annealed coating on CFS members as an acceptable substitute for hot-dip galvanizing [Ref. 20.2]. To apply galv-annealed coating, the member is first hot-dip galvanized, and then annealed by heating it to a temperature of 1,000°F. This results in the formation of a zinc-iron alloy on the surface of the member so that the coating contains 90% zinc and 10% iron, as compared with 100% zinc on a hot-dip galvanized member.

The primary advantage of galv-annealed coating for CFS members is the improvement of weldability. So, it is generally considered for heavier CFS sections that require welding. A galv-annealed coating is designated as A40, A60, etc. A shared coating designation is CP, where "CP" implies corrosion protection. Thus, a shared designation for G40 and A40 is CP40.

SHEET THICKNESS OF CFS MEMBERS

The thickness of steel sheet used in forming CFS members was earlier specified by gauge number, which was inconvenient because one had to refer to a table to obtain the actual thickness of sheet from the gauge number. Modern specifications require CFS sheet thickness to be stated in mils (where 1 mil = 0.001 in.). The reason for the change to actual thickness is that for determining the strength of a CFS member and for other structural calculations, actual thickness of sheet steel is needed. However, gauge number specification is still used in addition to actual thickness. Note that the higher the gauge number, the thinner the sheet. Thus, a 20-gauge sheet steel is thicker than a 22-gauge sheet steel.

The thickness of steel sheet used for CFS members varies from18 mil to 118 mil. EQ studs can be thinner than18 mil (see Figure 20.12). Thickness values represent bare steel thickness and do not include the thickness of corrosion protection.

YIELD STRENGTH OF CFS SHEET

CFS members are made from sheet steel of various yield strengths. The most commonly used yield strengths are 33 ksi and 50 ksi. EQ studs are generally made of steel sheet whose yield strength exceeds 50 ksi, as explained in Section 20.4.

20.2 CROSS-SECTIONAL PROFILES OF CFS MEMBERS

The commonly used cross-sectional profiles of CFS framing members are grouped under the following four categories:

- *C-shape* is used for studs, Figure 20.4. In the standard designation system, a C-shape section is identified by the symbol "S", derived from the term "stud", although the same cross-sectional profile is also used for floor joists and (roof) rafters.
- *U-shape* is used for top and bottom tracks in walls. They are also used in window sills, lintel headers, and rim joists. The symbol used for designating a U-shape section is "T", derived from the tern "track".
- Another *U-shape* profile, used as bridging channels, forms a different category because of its entirely different function from the tracks. The symbol used for designating bridging channels is "U".
- Several CFS sections, used for securing a finish material, insulation, etc., are grouped in a miscellaneous category referred to as *furring sections*, symbolized by "F".

The term "STUF" is often invoked to recall the symbols—S for studs, T for tracks, U for bridging channels, and F for furring sections.

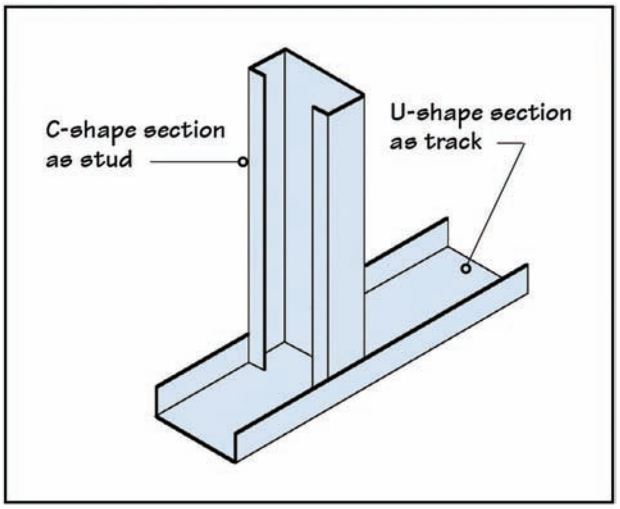


FIGURE 20.4 Two most commonly used CFS cross-sectional profiles—a C-shape section (used for studs, floor joists, and rafters), and a U-shape section—used for top and bottom tracks in walls.

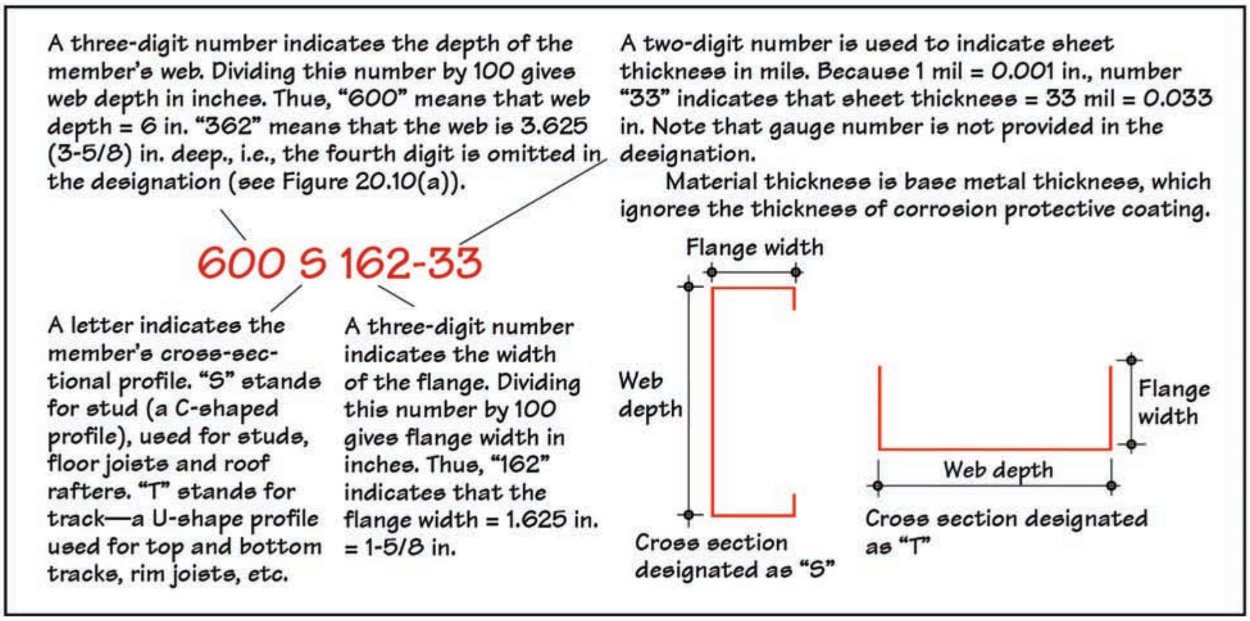
DETAILED DESIGNATION OF CFS MEMBERS

The Steel Stud Manufacturers Association (SSMA), an organization representing the CFS industry, identifies the four cross-sectional profiles listed previously by a standard designation, which provides four items of information as described here, and illustrated in Figure 20.5.

- *Web depth*—given by a three-digit number.
- *Cross-sectional profile*—given by letter "S", "T", "U", or "F".
- *Flange width*—given by a three-digit number.
- *Sheet thickness*—given by a two-digit number.

Thus, as shown in Figure 20.5, a member identified as "600 S162-33" means that it is a stud with a depth of 6.00 in., flange width of 1.62 in. (actually, 1.625 = $1\frac{5}{8}$ in.), and sheet thickness of 33 mil (20-gauge STR). The same designation is used for a floor joist or roof rafter because they are also C-shaped members.

The designation "362 T 125-27" means that it is track section with 3.625 in. $\left(3\frac{5}{8}\text{ in.}\right)$ deep web, 1.25 in. $\left(1\frac{1}{4}\text{ in.}\right)$ flange width, and 27 mil (22 gauge) sheet thickness. Similarly, the


A three-digit number indicates the depth of the member's web. Dividing this number by 100 gives web depth in inches. Thus, "600" means that web depth = 6 in. "362" means that the web is 3.625 (3-5/8) in. deep., i.e., the fourth digit is omitted in the designation (see Figure 20.10(a)).

A two-digit number is used to indicate sheet thickness in mils. Because 1 mil = 0.001 in., number "33" indicates that sheet thickness = 33 mil = 0.033 in. Note that gauge number is not provided in the designation.

Material thickness is base metal thickness, which ignores the thickness of corrosion protective coating.

A letter indicates the member's cross-sectional profile. "S" stands for stud (a C-shaped profile), used for studs, floor joists and roof rafters. "T" stands for track—a U-shape profile used for top and bottom tracks, rim joists, etc.

A three-digit number indicates the width of the flange. Dividing this number by 100 gives flange width in inches. Thus, "162" indicates that the flange width = 1.625 in. = 1-5/8 in.

600 S 162-33
Flange width
Web depth
Cross section designated as "S"
Flange width
Web depth
Cross section designated as "T"

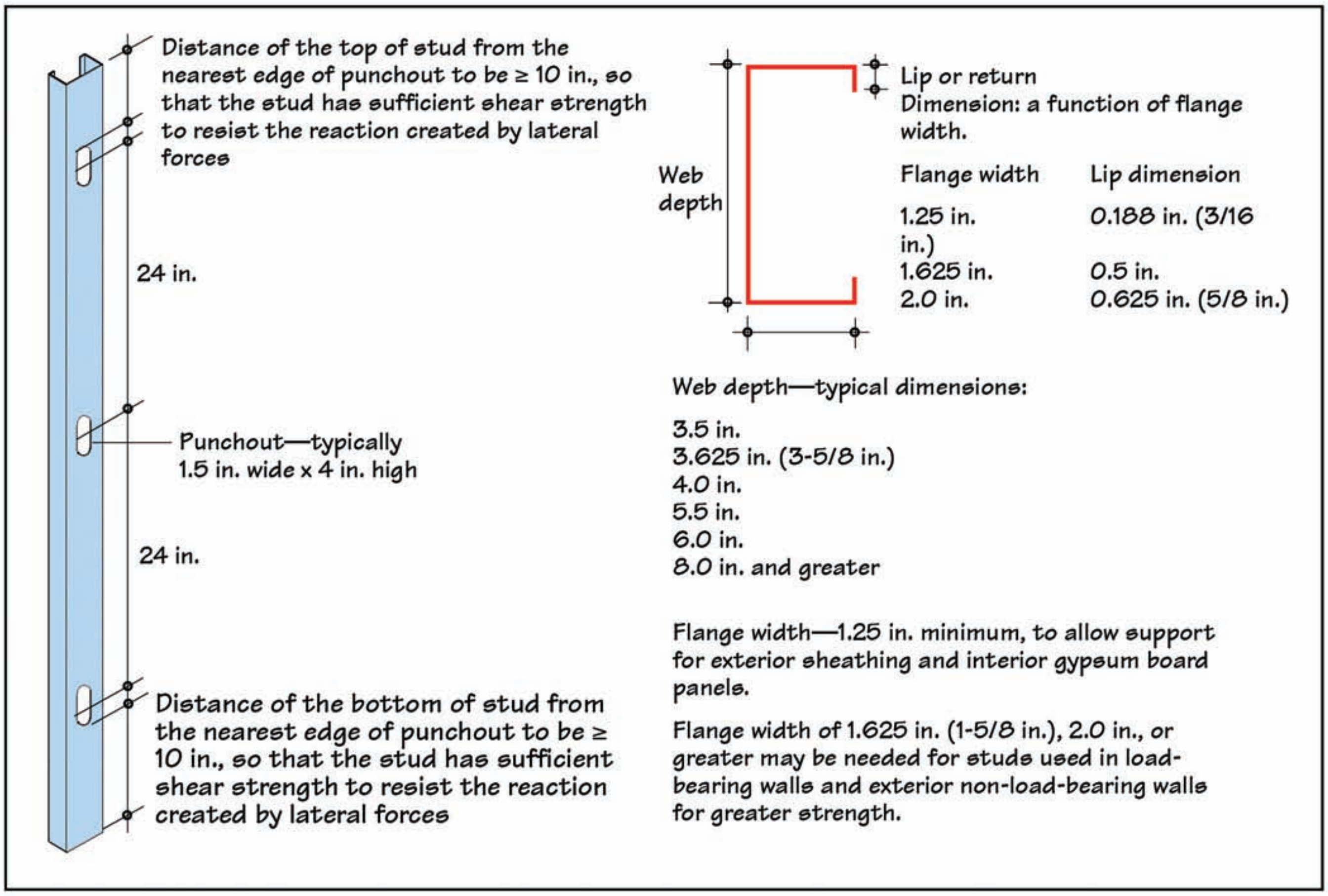
FIGURE 20.5 Designation system for identifying CFS members [Ref. 20.2].

designation "150 U 50-54" indicates a bridging channel with web depth of 1.5 in. $\left(1\frac{1}{2}\text{ in.}\right)$ and flange width of 0.5 in. $\left(\frac{1}{2}\text{ in.}\right)$, and sheet thickness of 54 mil.

STUDS AND TRACKS

The cross-sectional profiles of C-shape and U-shape are similar to each other as both consist of two flanges and one web. The only difference between them is that the flanges of a C-shape have returns, which gives a C-shaped cross section greater strength and greater resistance against bending and rotation. Therefore, C-shaped cross sections are used in studs, floor joists, and (roof) rafters.

The studs are punched with holes at 24 in. on center, Figure 20.6. Punched holes allow the passage of electrical conduits and other utility lines through the wall, Figure 20.7. They also allow the use of bridging channels.


Distance of the top of stud from the nearest edge of punchout to be ≥ 10 in., so that the stud has sufficient shear strength to resist the reaction created by lateral forces

Punchout—typically 1.5 in. wide x 4 in. high

Distance of the bottom of stud from the nearest edge of punchout to be ≥ 10 in., so that the stud has sufficient shear strength to resist the reaction created by lateral forces

Lip or return
Dimension: a function of flange width.

Flange width	Lip dimension
1.25 in.	0.188 in. (3/16 in.)
1.625 in.	0.5 in.
2.0 in.	0.625 in. (5/8 in.)

Web depth—typical dimensions:
3.5 in.
3.625 in. (3-5/8 in.)
4.0 in.
5.5 in.
6.0 in.
8.0 in. and greater

Flange width—1.25 in. minimum, to allow support for exterior sheathing and interior gypsum board panels.

Flange width of 1.625 in. (1-5/8 in.), 2.0 in., or greater may be needed for studs used in load-bearing walls and exterior non-load-bearing walls for greater strength.

FIGURE 20.6 Typical cross-sectional dimensions of studs and the spacing of punched holes.

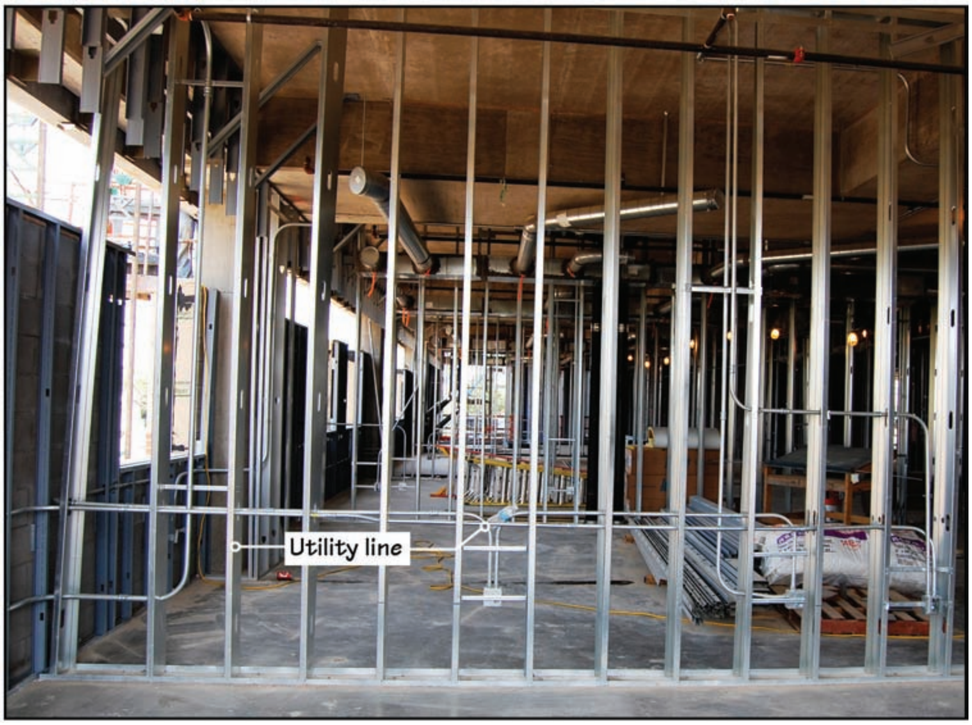


FIGURE 20.7 Punched holes in studs allow the passage of utility lines.

The tracks match the studs so that the studs fit within the tracks. They run at the top and bottom of the studs, simulating the top and bottom plates in wood frame construction. Studs and tracks used in a wall assembly are of the same sheet thickness (gauge), unless structural considerations require otherwise.

BRIDGING CHANNELS

Because of their thin walls and open cross section, CFS studs are prone to twisting (rotation) and buckling under the loads (see Figure 20.16). A closed section, such as a tube, is less prone to twisting. Bridging channels provide bracing to increase the resistance of members against these modes of failure. They are U-shaped, typically with $1\frac{1}{2}$-in.-deep webs, 54-mil (16-gauge) sheet thickness, and fit within the punched holes in studs, Figure 20.8.

Bridging channels are screw connected to the studs with clip angles (typically 16 gauge, $1\frac{1}{2}$ in. equal leg angles) to provide a relatively rigid connection between the studs and the channels, and thereby increase the rotational stiffness of studs. Bridging channels are used only in non-load-bearing walls (interior partitions and exterior cladding walls), and cannot be used in load-bearing walls because they do not extend the full width of studs and are, therefore, unable to brace the wall against buckling caused by axial compression.

They are also inadequate in non-load-bearing walls with studs whose web depth is greater than 6 in. (such walls are uncommon). As discussed in Section 20.5, bridging channels are unnecessary in a non-load-bearing wall if the wall is braced by full-height gypsum board or gypsum sheathing panels.

FURRING SECTIONS

Three types of furring sections are in common use: (a) hat channels, (b) resilient channels, and (c) Z-sections, Figure 20.9. A hat channel is generally used on the interior face of masonry covered with gypsum board (see Figure 28.20(b)). A resilient channel is used to increase the airborne sound insulation of a wall or floor (see Chapter 8). A Z-section is generally used to hold rigid board insulation on the inside or outside face of an exterior wall.

IDENTIFICATION MARK ON CFS MEMBERS

The cross-sectional size, type of framing member (stud or track), material specifications, and the manufacturer's name (logo or initials) are printed on each individual CFS member, generally 48 in., not to exceed 96 in., center-to-center spacing [Ref. 20.3]. A typical identification mark is shown in Figure 20.10(a). This gives the member's designation (web depth, flange width, steel sheet thickness, etc.), corrosion protection, and yield strength. Additionally, a bundle of like members is marked or tagged, giving the number of members, length of each member, and member designation, Fig. 20.10(b).

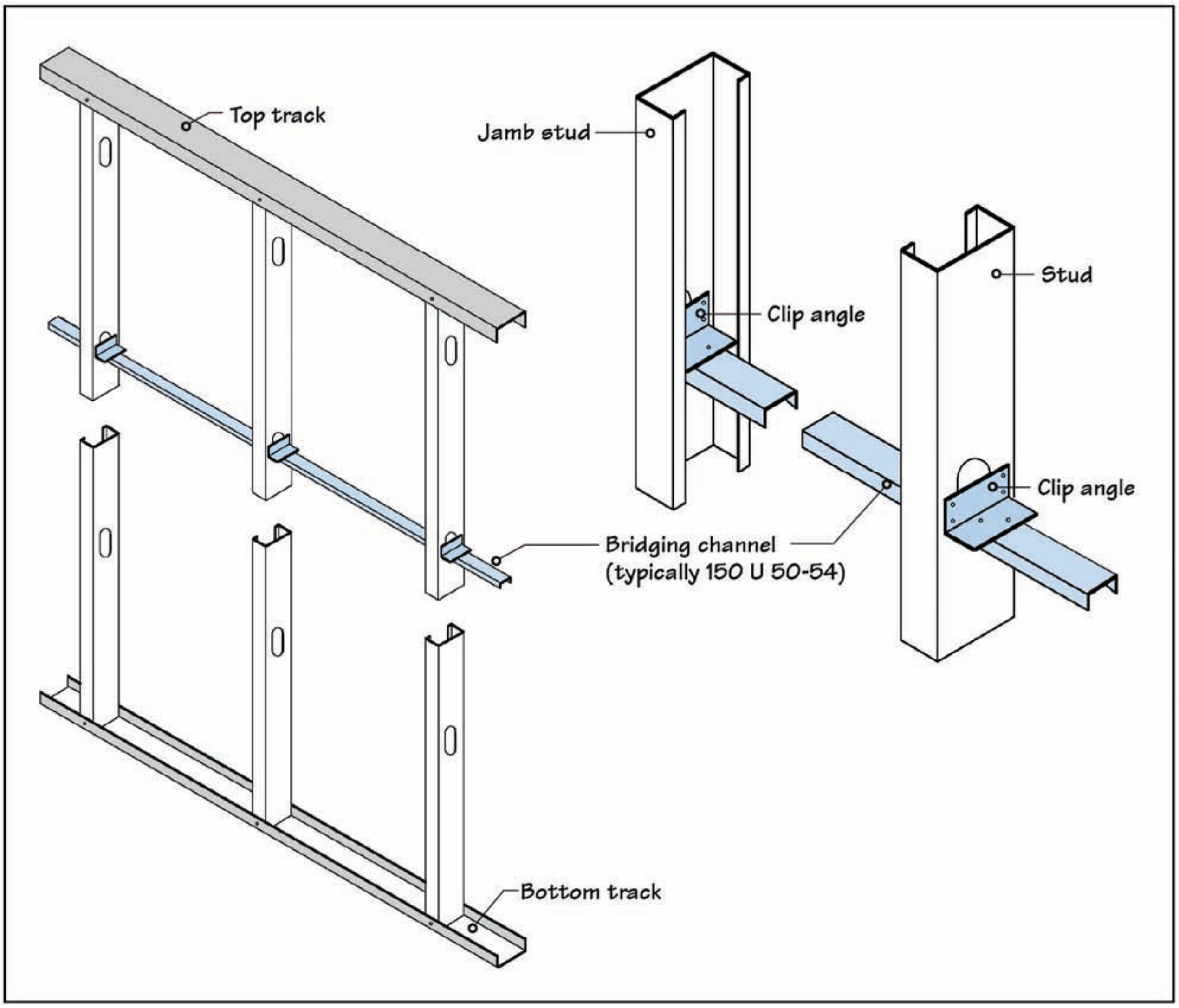

Top track
Jamb stud
Stud
Clip angle
Clip angle
Bridging channel
(typically 150 U 50-54)
Bottom track

FIGURE 20.8 Punched holes in studs and bridging channels.

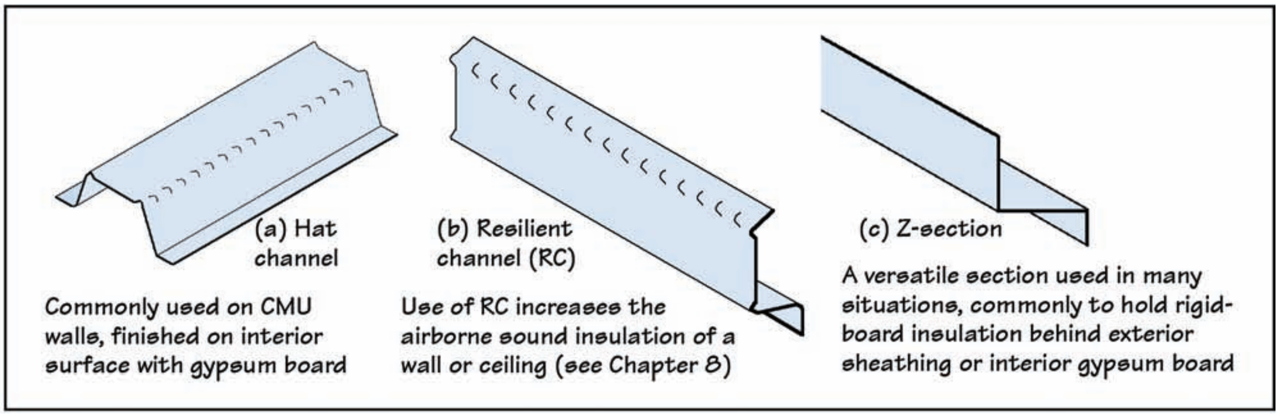
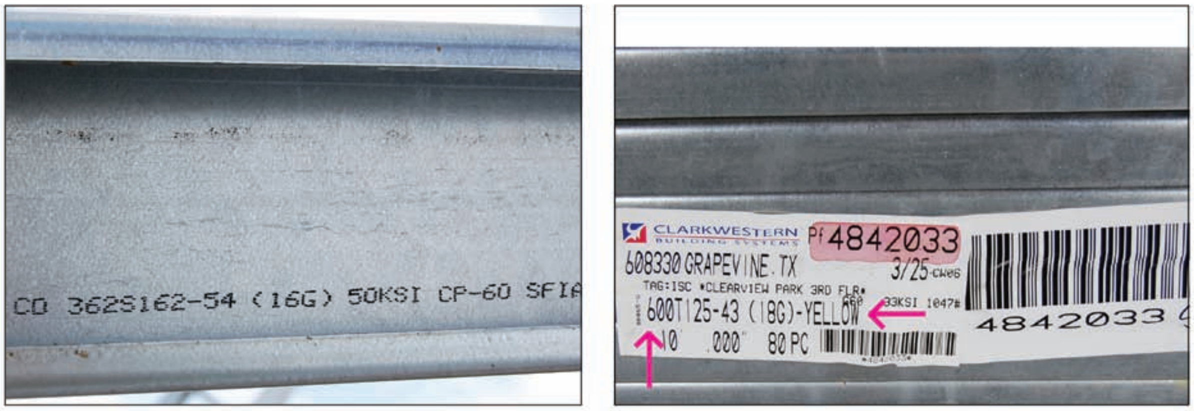

(a) Hat channel
Commonly used on CMU walls, finished on interior surface with gypsum board
(b) Resilient channel (RC)
Use of RC increases the airborne sound insulation of a wall or ceiling (see Chapter 8)
(c) Z-section
A versatile section used in many situations, commonly to hold rigid-board insulation behind exterior sheathing or interior gypsum board

FIGURE 20.9 Commonly used CFS furring sections.

20.3 STRUCTURAL AND NONSTRUCTURAL CFS MEMBERS

The construction industry divides "S" and "T" sections in two categories, referred to as: (a) structural members and (b) nonstructural members. The nonstructural members are used for interior drywall partitions and ceilings, while the structural members are used for load-bearing walls and the framing of the backup wall for exterior cladding. The distinction between the structural and nonstructural categories is based on performance requirements, as well as construction contracting convenience.

Drywall partitions require smaller sections, lower yield strength steel, and a lower level of corrosion protection. Additionally, because the consequence of structural failure of a partition is less severe than that of exterior cladding or a load-bearing assembly, a lower level


CD 362S162-54 (16G) 50KSI CP-60 SFIA
CLARKWESTERN BUILDING SYSTEMS
Pf 4842033
608330 GRAPEVINE, TX
3/25
TAG:ISC *CLEARVIEW PARK 3RD FLR*
600T125-43 (18G)-YELLOW
33KSI 1047#
10' .000" 80 PC
4842033

(a) Identification mark on an individual CFS member
"CD" implies ClarkDietrich (manufacturer)
"362S162-54" represents member designation (see Figure 20.5)
"16G" implies 16-gauge sheet thickness, equivalent of 54 mil
"50 ksi" represents yield strength of steel
"CP60" represents corrosion protection of member (see Section 20.1)

(b) Identification mark on a bundle of like members.

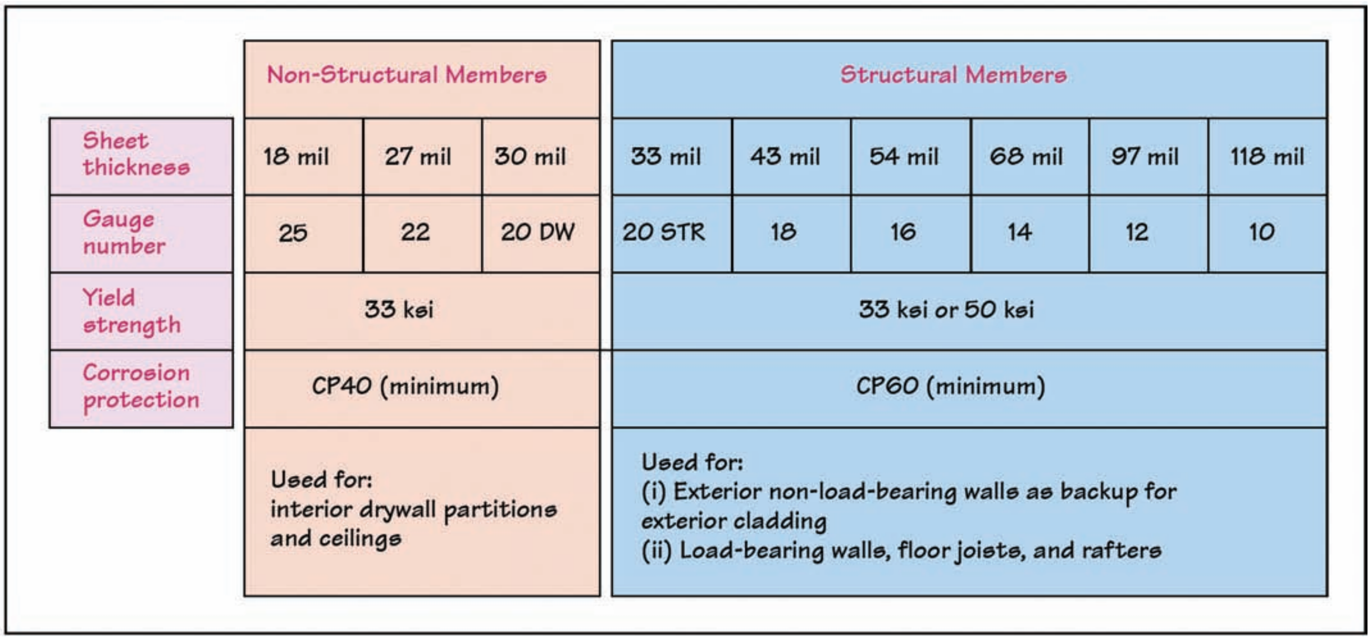
FIGURE 20.10 Identification marks on: **(a)** an individual CFS member and **(b)** a bundle of like members.

of structural reliability (structural safety provision) is used in the design of nonstructural members, as compared with structural members.

MASTERFORMAT DIVISION 09 (FINISHES) AND DIVISION 05 (METALS)

Another reason for the distinction between the two categories is that the construction of drywall partitions and ceilings in new construction and remodeling of commercial and industrial interiors (caused by the change of tenancy or the function of the interior space) has developed into a specialized trade. In this trade, the entire work of constructing partitions and ceilings is undertaken on turnkey basis by drywall contractors. The work, involving the framing of CFS members, hanging of drywall, tape, bed, texture, and painting of wall and ceiling surfaces, is considered as finishes in construction industry. Therefore, all material specifications, including those of CFS members, are included in MasterFormat Division 09 (Finishes).

Thus, CFS framing for interior partitions is referred to as *Nonstructural Metal Framing* in MasterFormat Division 09. By contrast, specifications for CFS framing for load-bearing applications and non-load-bearing exterior walls are included in MasterFormat Division 05 and are referred to as *Cold-Formed Metal Framing*.



	Non-Structural Members			Structural Members					
Sheet thickness	18 mil	27 mil	30 mil	33 mil	43 mil	54 mil	68 mil	97 mil	118 mil
Gauge number	25	22	20 DW	20 STR	18	16	14	12	10
Yield strength	33 ksi			33 ksi or 50 ksi					
Corrosion protection	CP40 (minimum)			CP60 (minimum)					
	Used for: interior drywall partitions and ceilings			Used for: (i) Exterior non-load-bearing walls as backup for exterior cladding (ii) Load-bearing walls, floor joists, and rafters					

FIGURE 20.11 CFS members designated as structural and nonstructural members, their applications, and important specifications [Ref. 20.4].

DISTINGUISHING FEATURES OF STRUCTURAL AND NONSTRUCTURAL MEMBERS

The important distinguishing features between the two categories are shown in Figure 20.11. However, it is important to note that the distinction between the two categories is not watertight. In other words, if a drywall partition, because of its unusually large height or greater load demand requires the use of structural sections, that will be in order.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. Cold-formed steel (CFS) is used in load-bearing walls, non-load-bearing walls, floors, and roofs.
a. True **b.** False

2. The use of CFS members in interior partitions is generally in buildings of
a. Type I construction.
b. Type II construction.
c. Type III construction.
d. Types II and III construction.
e. Types I and II construction.

3. CFS members are generally used as framing members in exterior wall cladding in buildings of
a. Types I, II, and III construction.
b. Types II, III, and IV construction.
c. Types III, IV, and V construction.
d. Types I, II, III, IV, and V construction.
e. none of the above.

4. The gravity load supported by CFS members, used in the framing of the backup wall for exterior cladding, is small.
a. True **b.** False

5. The use of CFS, as an alternative to lumber, in load-bearing residential applications, has found favor in some warm, humid areas of United States because CFS is
a. noncombustible.
b. heavier, and hence stronger.
c. lower in labor and installation cost.
d. more durable against termite and fungal attack.
e. all of the above.

6. The amount of corrosion protection required in CFS members is generally
a. CP30.
b. CP40.
c. CP50.
d. CP60.
e. varies with the application.

7. The terms G40 and CP40 refer to the same property of CFS members.
a. True **b.** False

8. The yield strength of CFS members used for interior partitions is generally
a. 20 ksi.
b. 30 ksi.
c. 40 ksi.
d. 50 ksi.
e. none of the above.

9. The yield strength of CFS members used in load-bearing applications is generally
a. 20 ksi.
b. 30 ksi.
c. 40 ksi.
d. 50 ksi.
e. none of the above.

10. A 20-gauge sheet steel is thicker than 22-gauge sheet steel.
a. True **b.** False

11. CFS studs are C-shaped.
a. True **b.** False

12. Punchouts in CFS studs are generally spaced
a. 48 in. on center.
b. 36 in. o.c.
c. 24 in. on center.
d. 12 in. on center.
e. none of the above.

13. In the identification mark on a CFS member "362S125-30 (33) G40", the letter S implies that
a. it is an S-shaped member.
b. it is a straight, unbent member.
c. it can only be used for a single-story building.
d. it is made from steel with a strength of 362 ksi.
e. none of the above.

14. In the identification mark on a CFS member "362S125-30 (33) G40", the number 30 implies that
a. it is a 30-ft-long member.
b. it is a 30-in.-long member.
c. the thickness of steel used for the member is gauge 30.
d. the thickness of steel sheet used for the member is 0.030 in.
e. none of the above.

15. The use of bridging channels requires
a. punched studs.
b. unpunched studs.
c. punched tracks.
d. unpunched tracks.
e. none of the above.

16. Both a Z-shape CFS section and a hat section are referred to as furring CFS sections.
a. True **b.** False

20.4 EQUIVALENT (EQ) STUDS AND TRACKS

Recently, CFS industry has developed studs and tracks with their web surface stiffened by uniformly spaced surface deformations (in place of a smooth surface). The type of surface deformations vary with the manufacturer. Two types of surface deformations are common—diamond-shaped embossing or surface dimpling, Figure 20.12.

The increase in stiffness obtained from surface deformations on a steel sheet is similar to the corrugations on a cardboard sheet. Consequently, studs made from a thinner sheet with surface deformations can be structurally equivalent to those made from a thicker but a flat sheet. For example, studs made from a 15-mil-thick dimpled sheet steel have been found to be structurally "equal" to those made from an 18-mil-thick, smooth-surface (undimpled) sheet, giving 17% saving in steel.

CFS industry calls such studs as "EQ" studs. To obtain the same screw pull-out resistance from a thinner steel, the yield strength of steel used in EQ studs is higher—in excess of 50 ksi. Pull-out strength of sheet steel is an important requirement because CFS walls may have handrails and fixtures attached to them.

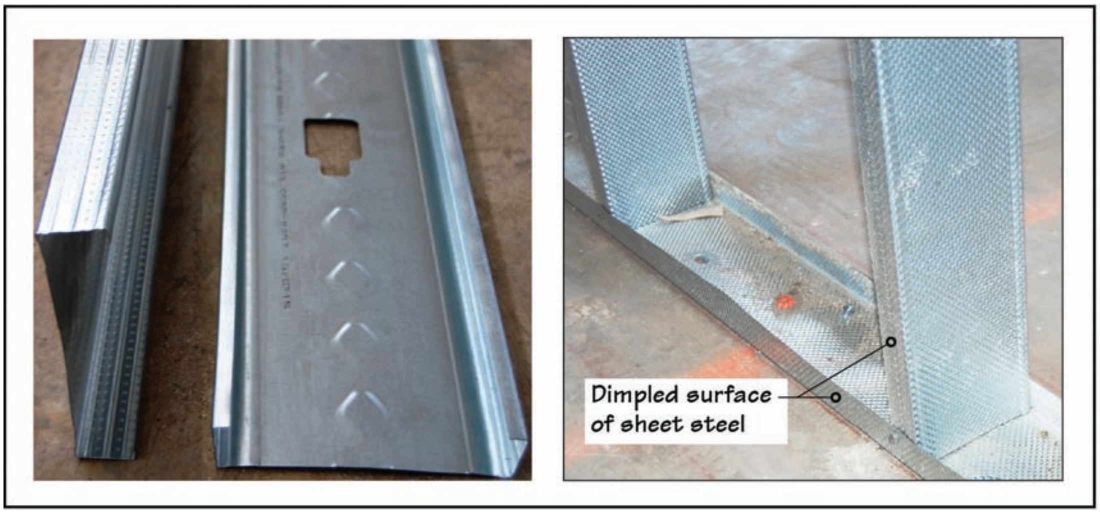


FIGURE 20.12 Two types of EQ studs and tracks with different styles of surface deformations—diamond-shaped embossing or surface dimpling.

Thus, EQ studs use less material, are lighter in weight, and therefore provide saving on transportation and installation. Additionally, extensive fire and acoustical testing has shown that EQ studs provide greater sound insulation and fire resistance. Manufacturers claim that EQ studs earn more LEED points. Currently, the use of EQ studs is limited to nonstructural members (i.e., interior drywall framing).

EQ studs are designated by the studs to which they are equivalent. For example, 362S125-EQ18 means that it is equivalent to a conventional stud that is $3\frac{5}{8}$ in. deep, which is made from 18-mil-thick sheet, although the actual thickness of sheet used is smaller than 18 mil.

20.5 CFS IN INTERIOR DRYWALL PARTITIONS

Gypsum board (drywall) interior partitions with CFS framing are constructed by first fastening the top and bottom tracks to the structure, Figure 20.13(a). With both tracks in place, studs are inserted between them and screw fastened to the tracks. Finally, drywall is screw attached to the studs, Figure 20.13(b).

LOADS ON AN INTERIOR PARTITION

A typical interior partition is subjected to gravity load from the self-weight of the wall, comprising CFS studs and drywall. The lateral load is due to incidental impact, slamming of doors, and pressurization due to HVAC and air infiltration through building envelope (air infiltration pressure can exceed HVAC pressure during extreme wind events). The building

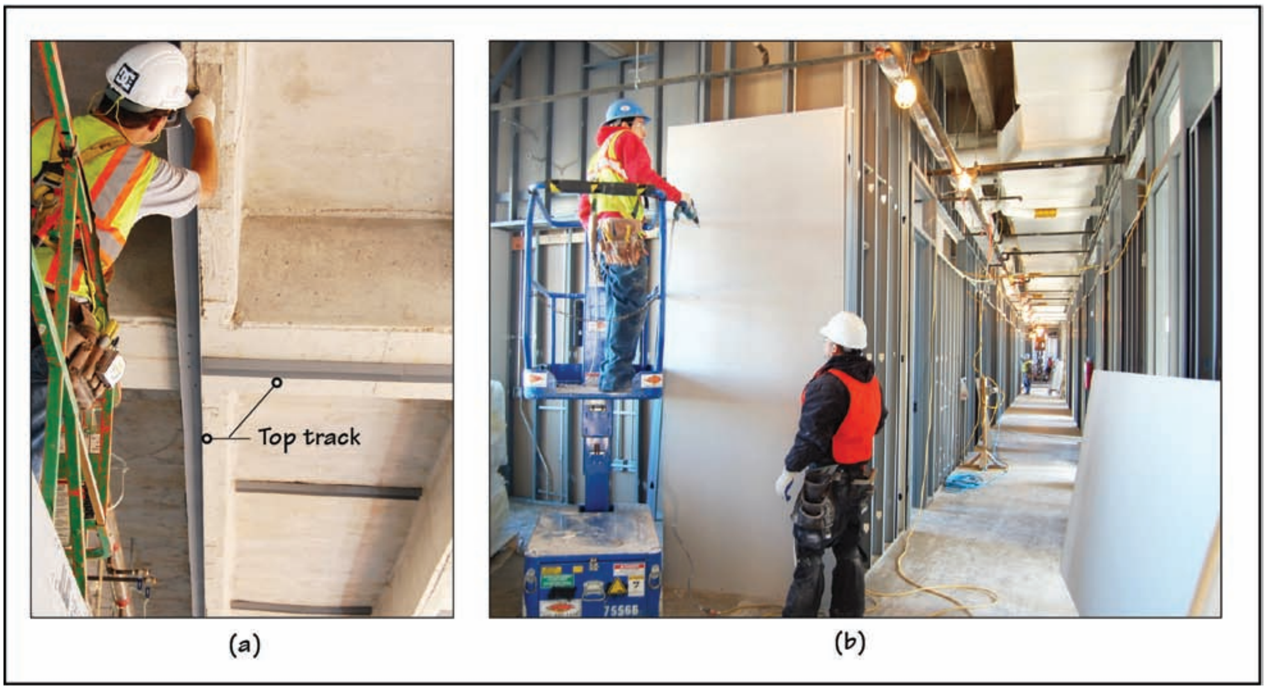


FIGURE 20.13 **(a)** A worker fastens the top track for an interior partition to the underside of a one-way concrete joist floor. **(b)** Gypsum board (drywall) being screw fastened to CFS framing of an interior partition.

codes require that the interior partitions be designed to resist a minimum of 5-psf lateral load [Ref. 20.5]. The minimum lateral load for shaft walls, enclosing the elevators, is 15 psf because of the higher air pressure created by the elevator moving through the shaft.

SIZE, SPACING, AND GAUGE OF STUDS FOR INTERIOR PARTITIONS

Because the gravity load on an interior partition is small (due only to partition's self-load), the structural design of partitions is based only on the lateral load, which creates bending stresses and deflection in studs. The size and gauge of studs is, therefore, based on the lateral load on studs and their center-to-center spacing. Note that as the center-to-center spacing of studs increases, the lateral load carried by each stud increases.

The size, spacing, and gauge of studs for an interior partition is generally selected from design tables provided by CFS manufacturers or the Steel Stud Manufacturers Association (SSMA)—an association representing the manufacturers. A sampling from these tables is shown in Table 20.1, which provides the limiting (maximum) height for a given stud, its gauge, and spacing for the following parameters.

Lateral Load: The design tables consider three different values for the lateral load—5 psf, 7.5 psf, and 10 psf. Although the use of 5 psf is permitted by the building code, the designer may use the higher load of 7.5 psf to enhance the safety margin that will allow for a small amount of unintended additional load. The manufacturers' or SSMA tables should be used for preliminary design. The final design should be engineered, particularly if the partitions support shelving and other fixtures.

Deflection: Three allowable deflection conditions—L/120, L/240, and L/360—are considered in the tables, where L represents stud span, that is, the distance between the top and bottom tracks. Building codes require that the maximum allowable deflection for an interior partition be limited to the values shown in Figure 20.14. Deflection is an important design criterion because gypsum board, being a brittle material, develops cracks under excessive deflection. Interior stucco plaster is even more brittle than gypsum board, and hence the maximum allowable deflection for plaster is lower than that for gypsum board. As shown in Figure 20.14, the code permits a maximum deflection of L/240 for drywall partitions.

Composite or Noncomposite Structural Behavior: The composite behavior implies that gypsum board panels and CFS studs act together in resisting the lateral load. In other words, each stud behaves like an I-section with the stud as the web and gypsum board panels as flanges of the I-section, Figure 20.15(a).

TABLE 20.1 LIMITING HEIGHTS OF SELECTED STUDS AND SHEET THICKNESS FOR INTERIOR DRYWALL PARTITIONS UNDER LATERAL LOADS OF 5 PSF, 7.5 PSF, AND 10 PSF; ASSUMES NONCOMPOSITE ACTION AND WALL BRACED AT MAXIMUM SPACING OF 48 IN.

		5 psf		7.5 psf		10 psf	
Stud designation	**Spacing (in.)**	**L/240**	**L/360**	**L/240**	**L/360**	**L/240**	**L/360**
350S125-27 (33)	12	16′–1″ (d)	14′–1″ (d)	14′–0″ (d)	12′–3″ (d)	12′–2″ (f)	11′–2″ (d)
	16	14′–7″ (d)	12′–10″ (d)	12′–2″ (f)	11′–2″ (d)	10′–7″ (f)	10′–1″ (d)
	24	12′–2″ (f)	11′–2″ (d)	9′–11″ (f)	9′–9″ (d)	8′–7″ (f)	8′–7″ (f)
350S125-30 (33)	12	16′–7″ (d)	14′–6″ (d)	14′–6″ (d)	12′–8″ (d)	13′–1″ (f)	11′–6″ (d)
	16	15′–1″ (d)	13′–2″ (d)	13′–1″ (f)	11′–6″ (d)	11′–4″ (f)	10′–6″ (d)
	24	13′–1″ (f)	11′–6″ (d)	10′–8″ (f)	10′–1″ (d)	9′–3″ (f)	9′–1″ (d)
362S125-27 (33)	12	16′–6″ (d)	14′–6″ (d)	14′–4″ (f)	12′–8″ (d)	12′–5″ (f)	11′–5″ (d)
	16	15′–0″ (d)	13′–2″ (d)	12′–5″ (f)	11′–5″ (d)	10′–9″ (f)	10′–5″ (d)
	24	12′–5″ (f)	11′–5″ (d)	10′–2″ (f)	10′–0″ (d)	8′–9″ (f)	8′–9″ (f)
362S125-30 (33)	12	17′–1″ (d)	14′–11″ (d)	14′–11″ (d)	13′–1″ (d)	13′–4″ (f)	11′–10″ (d)
	16	15′–6″ (d)	13′–7″ (d)	**13′–4″** (f)	11′–10″ (d)	11′–7″ (f)	10′–9″ (d)
	24	13′–4″ (f)	11′–10″ (f)	**10′–11″** (f)	10′–4″ (d)	9′–5″ (f)	9′–4″ (d)

Notes:
1. Letter (d) indicates that the limiting height is controlled by stud deflection, and (f) indicates that it is controlled by flexural stress in studs.
2. The number within parentheses for stud designation refers to the yield strength of sheet steel, that is, 33-ksi steel, commonly used for interior partitions (see Figures 2.5 and 20.11).
3. Red color values refer to Example 20.1.

Source: From Product Technical Information. Published by Steel Stud Manufacturers Association © 2010.

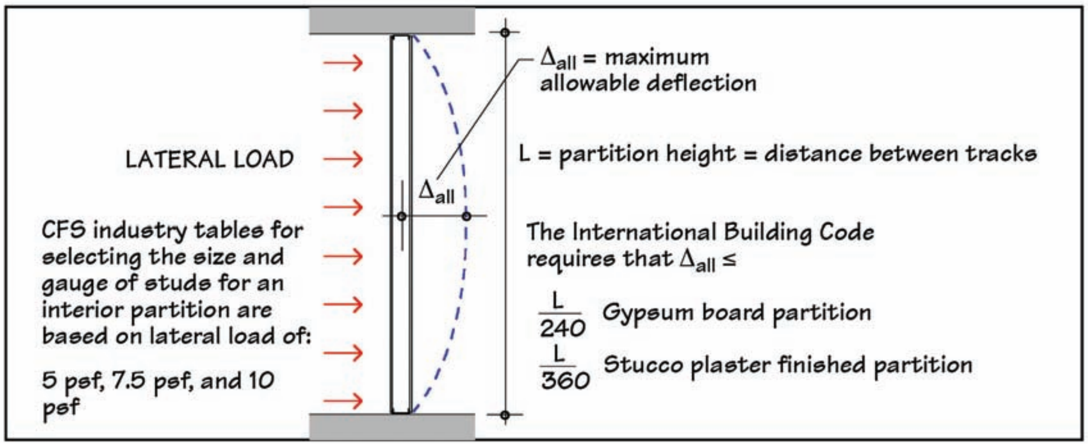

LATERAL LOAD
CFS industry tables for selecting the size and gauge of studs for an interior partition are based on lateral load of:
5 psf, 7.5 psf, and 10 psf
Δ_{all}
Δ_{all} = maximum allowable deflection
L = partition height = distance between tracks
The International Building Code requires that $\Delta_{all} \leq$
$\frac{L}{240}$ Gypsum board partition
$\frac{L}{360}$ Stucco plaster finished partition

FIGURE 20.14 Lateral load and deflection considerations for the design of an interior gypsum board partition.

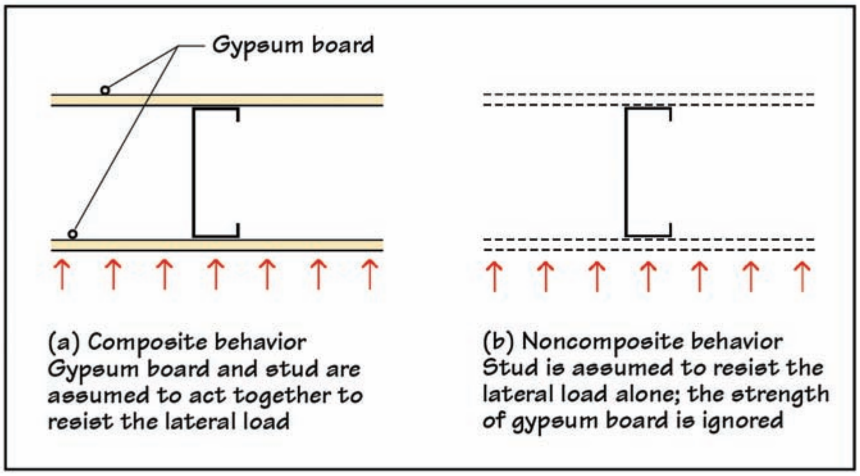

Gypsum board
(a) Composite behavior
Gypsum board and stud are assumed to act together to resist the lateral load
(b) Noncomposite behavior
Stud is assumed to resist the lateral load alone; the strength of gypsum board is ignored

FIGURE 20.15 Composite and noncomposite behavior of an interior gypsum board partition. Assuming a noncomposite behavior is conservative (i.e., safer).

Noncomposite behavior implies no contribution from gypsum board panels in resisting the lateral load, so that the strength of gypsum board is ignored, and all the lateral load is assumed to be resisted by the studs, Figure 20.15(b). Gypsum board simply transfers the load to the studs.

Composite behavior yields more economical design, but requires that gypsum board extend the full height of studs on both sides of the partition. In many situations, this is not practical and gypsum board does not extend the full wall height in order to allow HVAC ducts utility lines, and structural framing members to pass through stud spaces. Therefore, partial-height partitions are fairly common, necessitating the consideration of the noncomposite behavior. Even where the gypsum board extends the full height of partition, it is common to assume the noncomposite behavior because of any future alteration in the building, requiring the gypsum board to be cut short from its original full height. Note that the assumption of a noncomposite behavior is conservative.

Fully Braced Wall or Wall Braced by Bridging Channels: As stated in Section 20.2, CFS studs, being open and thin walled, are prone to rotation and buckling of the compression flange under lateral loads, Figure 20.16. Therefore, the studs must be braced against these forms of instability. The tables recognize two alternative methods to brace a CFS partition:

- Brace the wall with gypsum board over its full height on both sides, Figure 20.17(a). This is referred to as a *fully braced wall*, which qualifies it for the assumption of a composite behavior. A fully braced wall does not need bracing by bridging channels.
- If the gypsum board is not applied on both sides and over full wall height, bridging channels are required at 4 ft on center, Figure 20.17(b). As previously stated, such situations occur frequently because it is impractical to apply gypsum board over the wall's full height because of either the structural obstructions or (and) those created by MEP, Figure 20.18. In such situations, gypsum board terminates a little above the ceiling, leaving the space between the studs without gypsum board lining. Bridging channels are also required if the gypsum board is applied over the entire height of the wall on one side only, Figure 20.19.

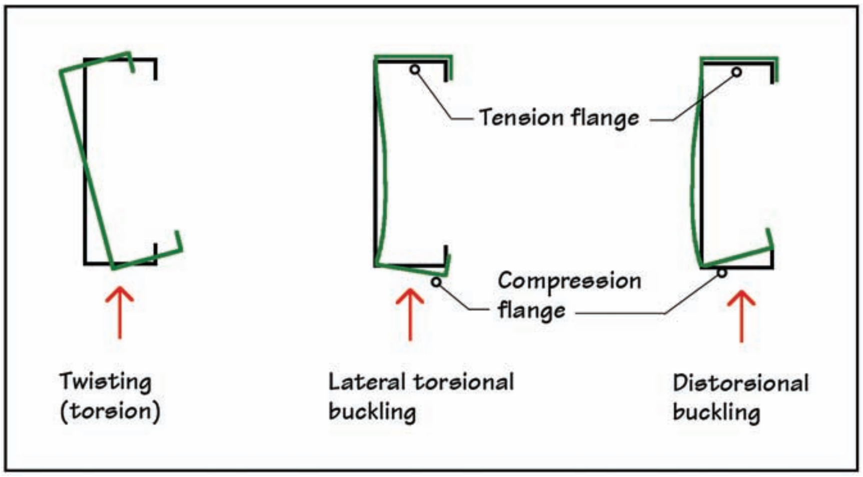

Tension flange
Compression
flange
Twisting
(torsion)
Lateral torsional
buckling
Distorsional
buckling

FIGURE 20.16 Various forms of lateral instability (twisting and buckling) of an unbraced stud under lateral load.

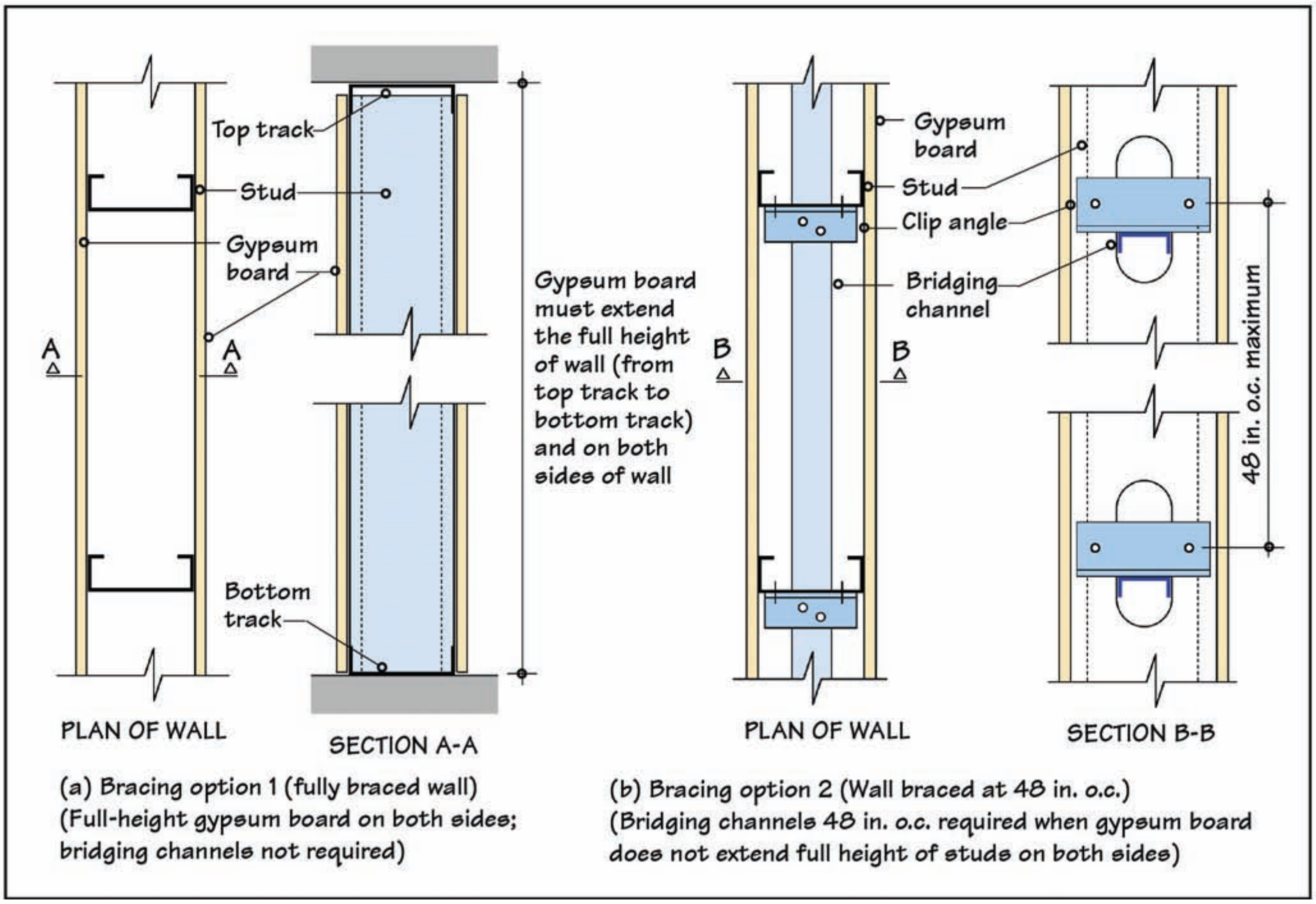

Top track
Stud
Gypsum
board
A
A
Bottom
track
PLAN OF WALL
SECTION A-A
Gypsum board
must extend
the full height
of wall (from
top track to
bottom track)
and on both
sides of wall
(a) Bracing option 1 (fully braced wall)
(Full-height gypsum board on both sides;
bridging channels not required)
Gypsum
board
Stud
Clip angle
Bridging
channel
B
B
48 in. o.c. maximum
PLAN OF WALL
SECTION B-B
(b) Bracing option 2 (Wall braced at 48 in. o.c.)
(Bridging channels 48 in. o.c. required when gypsum board
does not extend full height of studs on both sides)

FIGURE 20.17 Two alternative options for bracing the studs in an interior drywall partition.

Example 20.1 (Preliminary Sizing of CFS Members for Interior Partitions)

Determine if $3\frac{5}{8}$-in.-deep studs, 30 mil sheet thickness, 33 ksi yield strength [362S125-30 (33)], spaced 24 in. on center, are adequate for an office partition to resist a lateral load of 7.5 psf and the deflection not to exceed L/240. The height of the partition (bottom track to top track distance) is 12 ft. The wall is provided with bridging channels 48 in. o.c.

Solution

Stud specifications: 362S125-30 (33)
Spacing: 24 in. on center
Lateral load: 7.5 psf
Deflection: Not greater than (L/240), where L = height of partition

The limiting height for the studs and spacing given above is 10 ft 11 in. (see Table 20.1, column 5, last row in red color). Because this height <12 ft, it is not OK. If the stud spacing is reduced to 16 in., the limiting height is 13 ft 4 in., which being >12 ft, is OK.

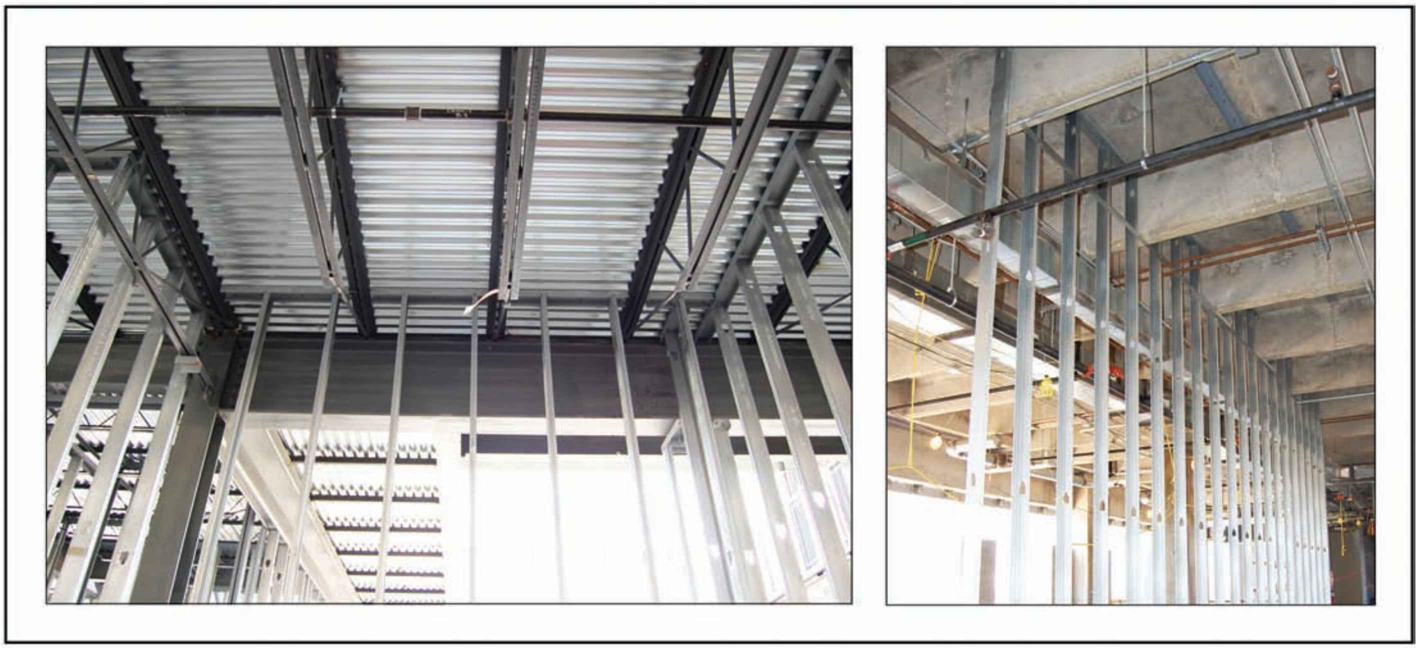
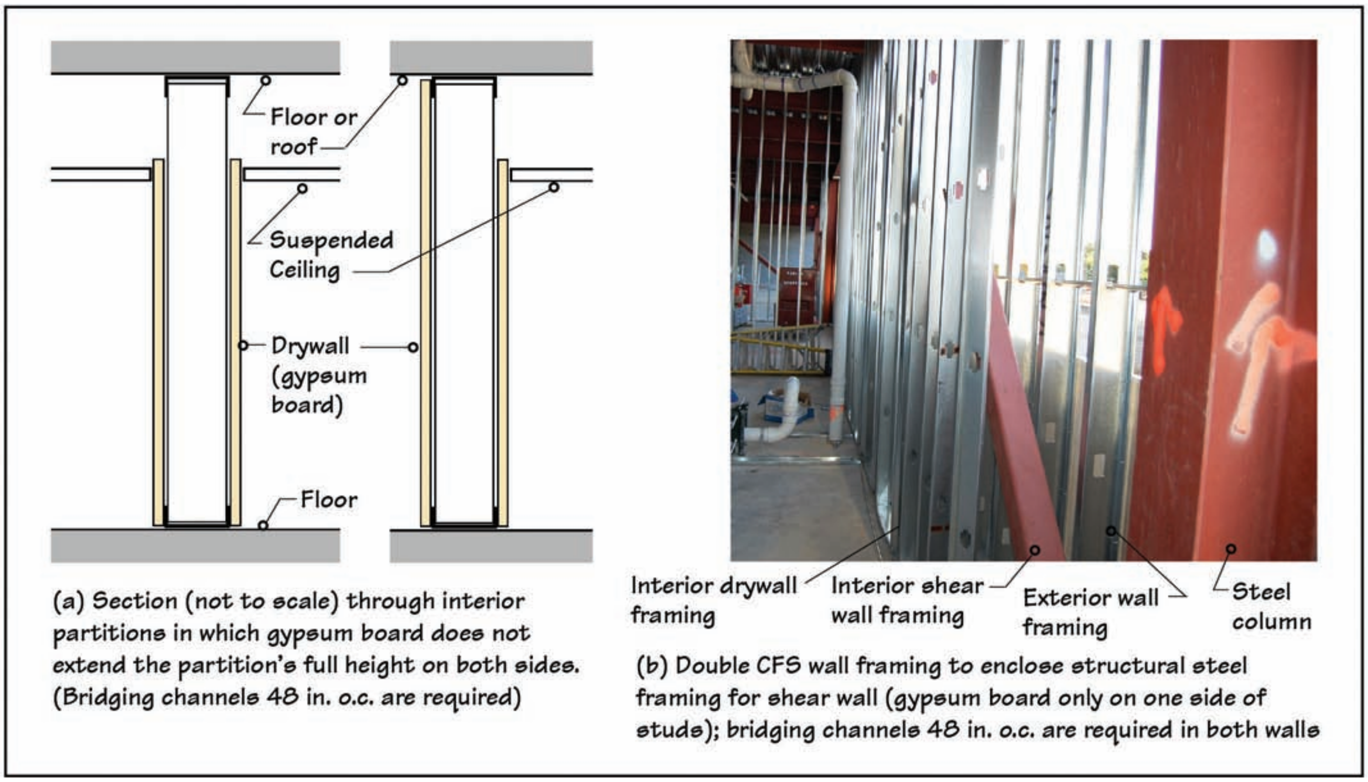


FIGURE 20.18 These images represent the reality of most interior CFS partitions, and highlight the difficulty in applying gypsum board to the partitions' full height because of several penetrations. The use of bridging channels is, therefore, common.



(a) Section (not to scale) through interior partitions in which gypsum board does not extend the partition's full height on both sides. (Bridging channels 48 in. o.c. are required)

(b) Double CFS wall framing to enclose structural steel framing for shear wall (gypsum board only on one side of studs); bridging channels 48 in. o.c. are required in both walls

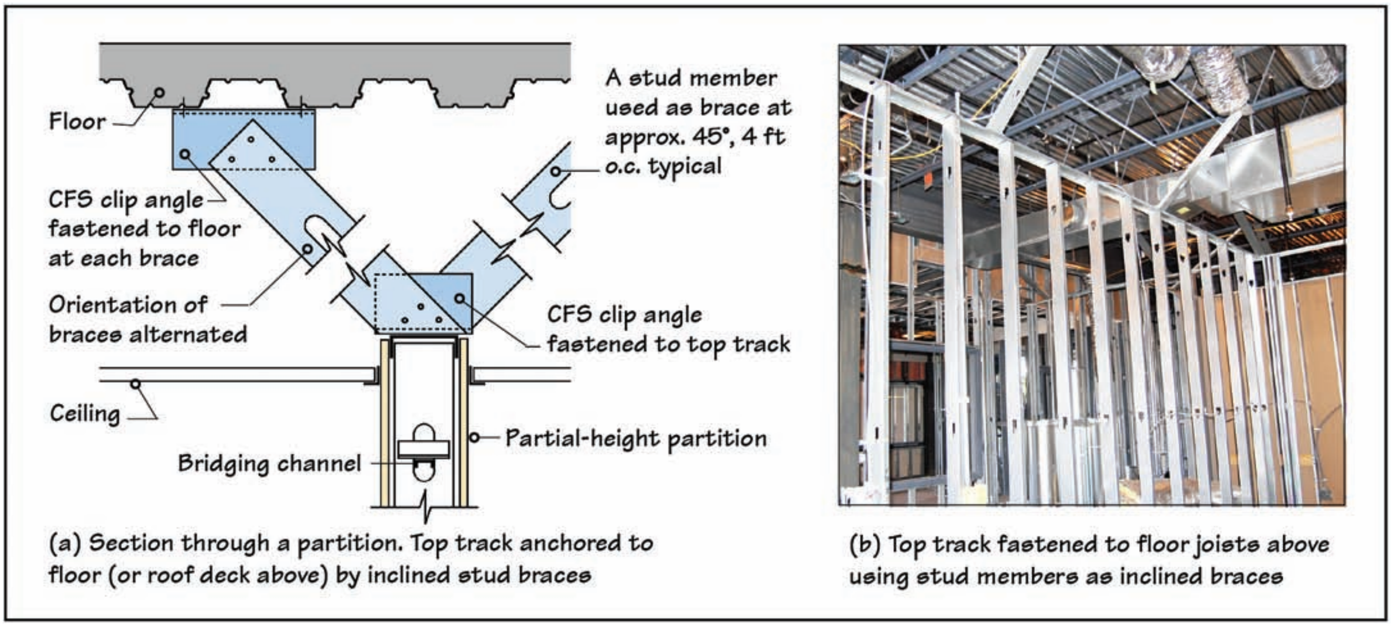
FIGURE 20.19 Commonly occurring interior drywall partitions where bridging channels are required.

20.6 INTERIOR DRYWALL PARTITIONS—DEFLECTION OF OVERHEAD STRUCTURE

It is obvious that the framing of an interior partition be supported at both the top and bottom of the wall. While the bottom track is always anchored to the floor, it is not always possible to anchor the top track to the overhead structure (e.g., a structural ceiling). In such a case, CFS braces, fastened to the overhead structure, are used to support the top track, Figure 20.20.

NON-FIRE-RATED PARTITION—HEAD-OF-WALL DETAIL

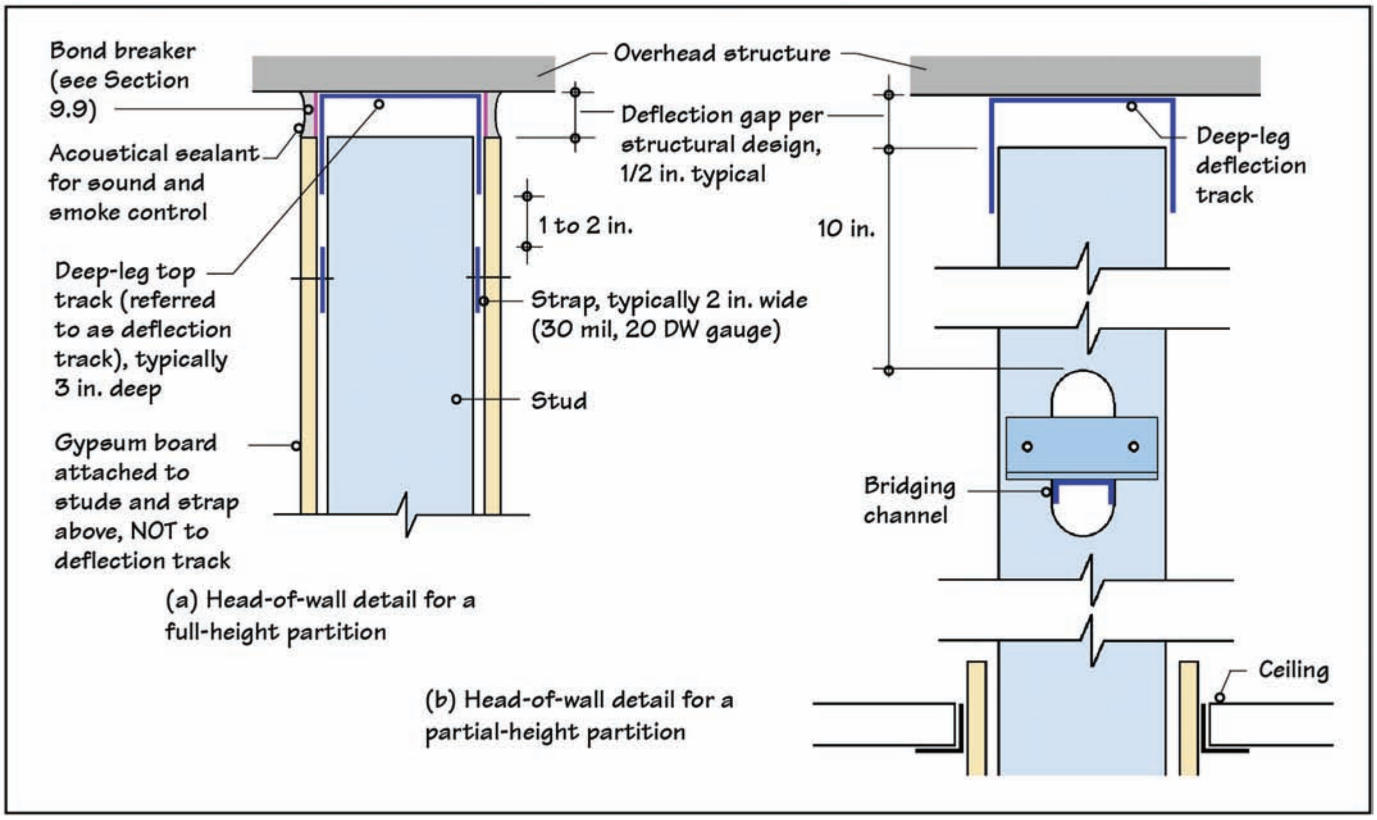
If the top track is anchored directly to the overhead floor/roof, it must be detailed to allow the overhead structure (floor or roof) to deflect unrestrained under the live load to prevent any load transferring to the partition. A deflection gap is provided at the top, requiring the


Floor
A stud member used as brace at approx. 45°, 4 ft o.c. typical
CFS clip angle fastened to floor at each brace
Orientation of braces alternated
CFS clip angle fastened to top track
Ceiling
Partial-height partition
Bridging channel

(a) Section through a partition. Top track anchored to floor (or roof deck above) by inclined stud braces

(b) Top track fastened to floor joists above using stud members as inclined braces

FIGURE 20.20 In situations where it is not possible to anchor the top track directly to overhead floor or roof, it is supported by inclined braces fastened to: **(a)** overhead floor or roof deck, or **(b)** to overhead floor or roof framing members.


Bond breaker (see Section 9.9)
Overhead structure
Acoustical sealant for sound and smoke control
Deflection gap per structural design, 1/2 in. typical
1 to 2 in.
Deep-leg top track (referred to as deflection track), typically 3 in. deep
Strap, typically 2 in. wide (30 mil, 20 DW gauge)
Stud
Gypsum board attached to studs and strap above, NOT to deflection track
Deep-leg deflection track
10 in.
Bridging channel
Ceiling

(a) Head-of-wall detail for a full-height partition

(b) Head-of-wall detail for a partial-height partition

FIGURE 20.21 Head-of-wall deflection systems for a non-fire-rated CFS interior partition.

use of a deep-leg top track. The two commonly used details, referred to as *head-of-wall details*, are shown in Figure 20.21. Gap depth depends on the calculated floor or roof deflection, which is typically limited by structural design to $\frac{1}{2}$ in.

In both details of Figure 20.21, the studs are not fastened to top track (referred to as the *deflection track*), which allows the track to slide up and down over the studs. In other words, the studs simply float within the deflection track. To ensure that the studs are aligned plumb, a continuous strap is fastened to studs a little below the deflection track, Figure 20.21(a). In walls where bridging channels are mandated (such as in a partial-height partition), one row of bridging channels must be located close to the deflection track, Figure 20.21(b). In place of the top row of bridging channels, a continuous strap such as that shown in Figure 20.21(a), may be used. Figure 20.22 in which two deep-leg nested tracks are used, is an alternative to the details of Figure 20.21.

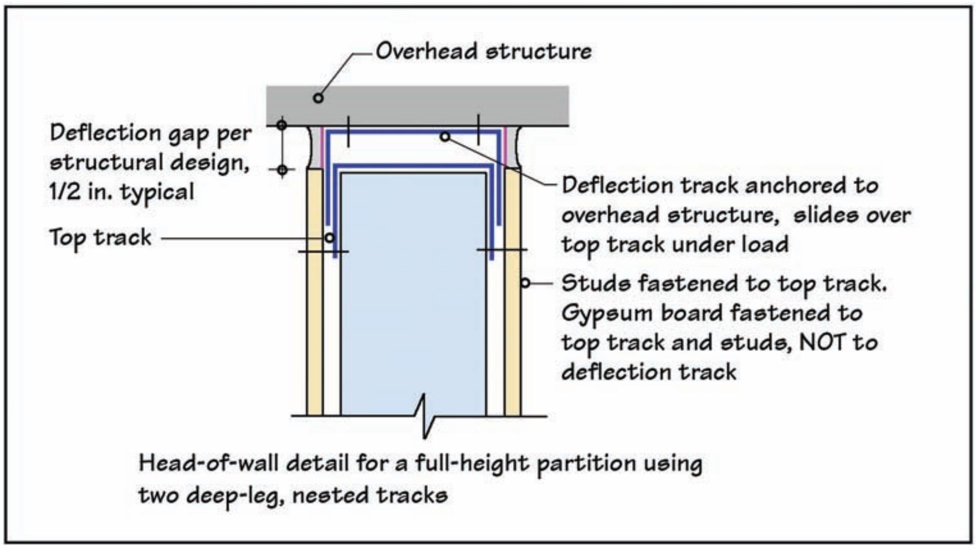

Overhead structure
Deflection gap per structural design, 1/2 in. typical
Top track
Deflection track anchored to overhead structure, slides over top track under load
Studs fastened to top track. Gypsum board fastened to top track and studs, NOT to deflection track
Head-of-wall detail for a full-height partition using two deep-leg, nested tracks

FIGURE 20.22 Head-of-wall deflection system for a non-fire-rated CFS interior partition, using two nested tracks—alternative to that of Figure 20.21(a).

FIRE-RATED PARTITION—HEAD-OF-WALL DETAIL

For a fire-rated CFS interior partition, Type X gypsum board is required over the wall's full height. The board's thickness is a function of the wall's fire rating. As described in Section 16.7, $\frac{5}{8}$-in.-thick Type X gypsum board on both sides of the wall gives a 1-h rating; two $\frac{5}{8}$-in.-thick Type X gypsum boards on both sides of the wall give a 2-h rating.

The head-of-wall detail is particularly important for a fire-rated wall, which must be detailed to ensure that it accommodates the vertical movement of the overhead structure and also provides the required fire resistance. Figure 20.23 shows details for a 1-h rated wall

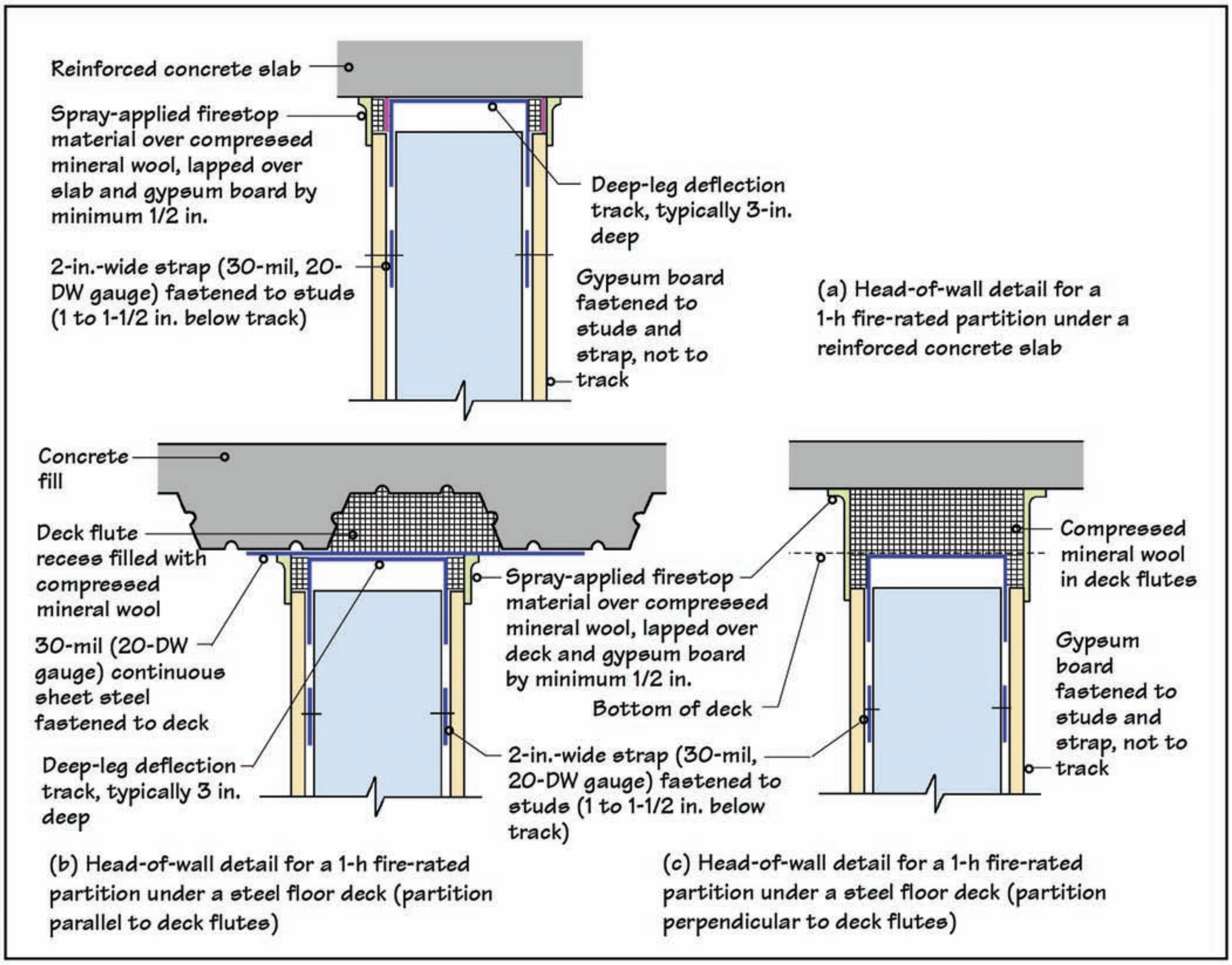

Reinforced concrete slab
Spray-applied firestop material over compressed mineral wool, lapped over slab and gypsum board by minimum 1/2 in.
2-in.-wide strap (30-mil, 20-DW gauge) fastened to studs (1 to 1-1/2 in. below track)
Deep-leg deflection track, typically 3-in. deep
Gypsum board fastened to studs and strap, not to track
(a) Head-of-wall detail for a 1-h fire-rated partition under a reinforced concrete slab
Concrete fill
Deck flute recess filled with compressed mineral wool
30-mil (20-DW gauge) continuous sheet steel fastened to deck
Deep-leg deflection track, typically 3 in. deep
Spray-applied firestop material over compressed mineral wool, lapped over deck and gypsum board by minimum 1/2 in.
Bottom of deck
2-in.-wide strap (30-mil, 20-DW gauge) fastened to studs (1 to 1-1/2 in. below track)
Compressed mineral wool in deck flutes
Gypsum board fastened to studs and strap, not to track
(b) Head-of-wall detail for a 1-h fire-rated partition under a steel floor deck (partition parallel to deck flutes)
(c) Head-of-wall detail for a 1-h fire-rated partition under a steel floor deck (partition perpendicular to deck flutes)

FIGURE 20.23 Head-of-wall deflection systems for a fire-rated CFS interior partition.

in typical concrete- and steel-frame structures. Note that these details share much in common with those shown in Figure 20.21.

SOUND INSULATION OF DRYWALL PARTITIONS

In many situations, an interior drywall is required to provide a minimum level of sound insulation through sound transmission class (STC) rating, see Chapter 8. Precise values of STC for assemblies using gypsum board should be obtained from Gypsum Association's publication titled *Fire Resistance Design Manual* [Ref. 20.7] which is referenced by the building codes.

In general, CFS walls provide a higher STC rating than wood stud walls of the same stud depth. This is due to the greater flexibility (hence, a greater damping) of CFS framing as compared with wood framing. For example, a wall with 2 × 4 wood studs with $\frac{5}{8}$-in.-thick gypsum board on both sides is a STC 37 wall, while a 3 $\frac{1}{2}$-in., 20-gauge CFS wall of the same construction gives STC 42. For the same reason, (greater flexibility), increasing stud spacing to 24 in. (from 16 in.) gives a slightly higher STC. Increasing the thickness of gypsum board, either by increasing board thickness or the number of boards, increases STC of both wood stud and CFS walls. The use of fiberglass in stud cavities and (or) the use of resilient channels also increases STC, see Section 8.4.

20.7 EXTERIOR NON-LOAD-BEARING (CURTAIN) WALLS

In structural steel- and concrete-frame buildings, the exterior walls are non-load-bearing, like the interior partitions. CFS framing in these walls is covered with fiberglass-mat-faced gypsum sheathing on the outside and conventional (paper-faced) gypsum board on the inside. The assembly, consisting of CFS framing, exterior sheathing, and interior gypsum board, functions as a backup wall to which any one (of the several types of) exterior wall cladding is applied. (Exterior wall cladding is covered in Chapters 27 to 29.) CFS framing for such walls is separated under the following two categories:

One- or Two-Story Buildings: The studs are continuous from the ground floor to the top of parapet, bypassing the roof and the intervening floor. To allow unrestrained live load deflection of floor and roof, the connection of studs to second floor and roof is a slip connection, using CFS slide clips with slotted holes, Figure 20.24.

NOTE

CFS Curtain Wall Framing

In the CFS industry, CFS framing for an exterior wall used as backup for exterior cladding is referred to as *curtain wall* framing, although the term *curtain wall* is technically incorrect here (see the definition of curtain wall in Expand Your Knowledge section in Chapter 27).

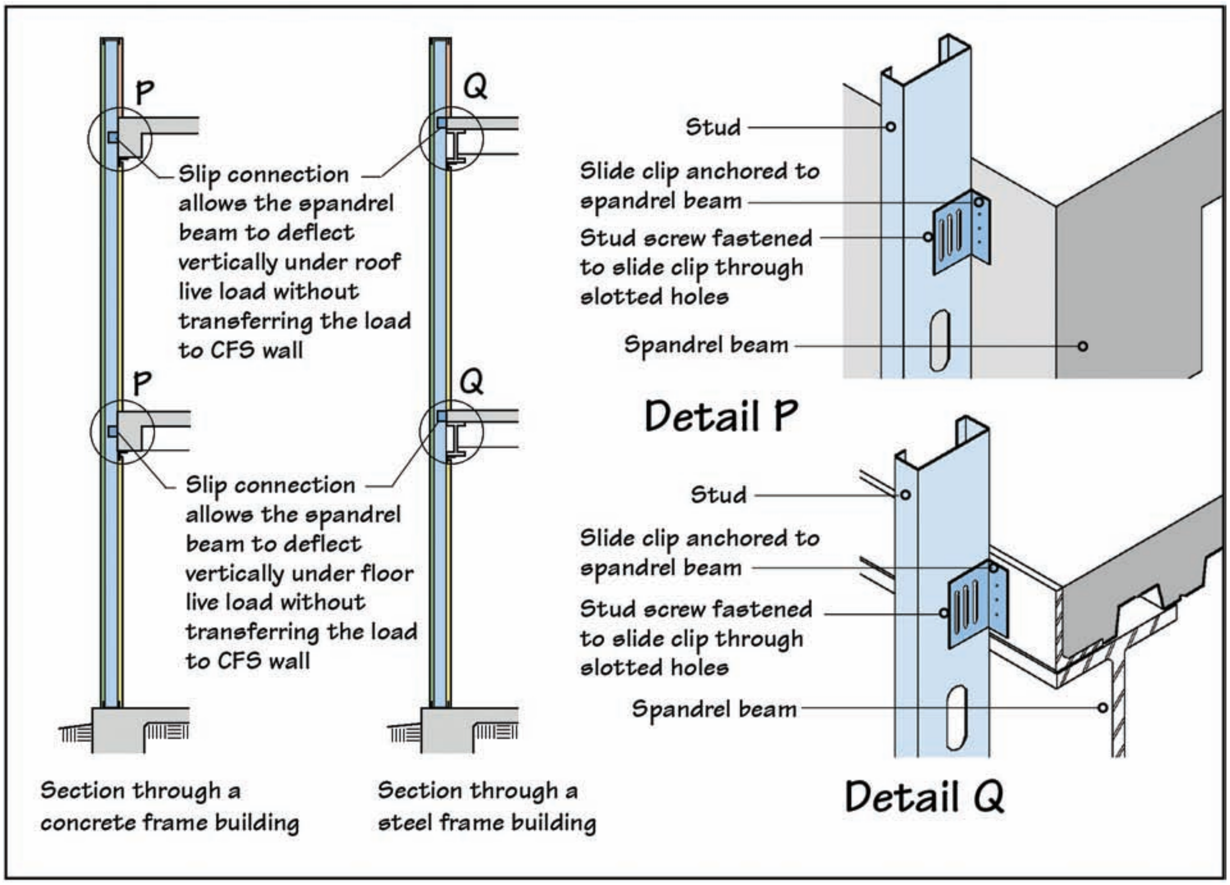

P
Slip connection allows the spandrel beam to deflect vertically under roof live load without transferring the load to CFS wall
P
Slip connection allows the spandrel beam to deflect vertically under floor live load without transferring the load to CFS wall
Q
Q
Section through a concrete frame building
Section through a steel frame building
Stud
Slide clip anchored to spandrel beam
Stud screw fastened to slide clip through slotted holes
Spandrel beam
Detail P
Stud
Slide clip anchored to spandrel beam
Stud screw fastened to slide clip through slotted holes
Spandrel beam
Detail Q

FIGURE 20.24 Exterior non-load-bearing CFS wall framing for a one- or two-story building. Note that the studs are continuous from ground floor to top of parapet, bypassing the intermediate floor and roof (see Figure 28.30). Each stud is anchored to the spandrel beam through a slip connection.

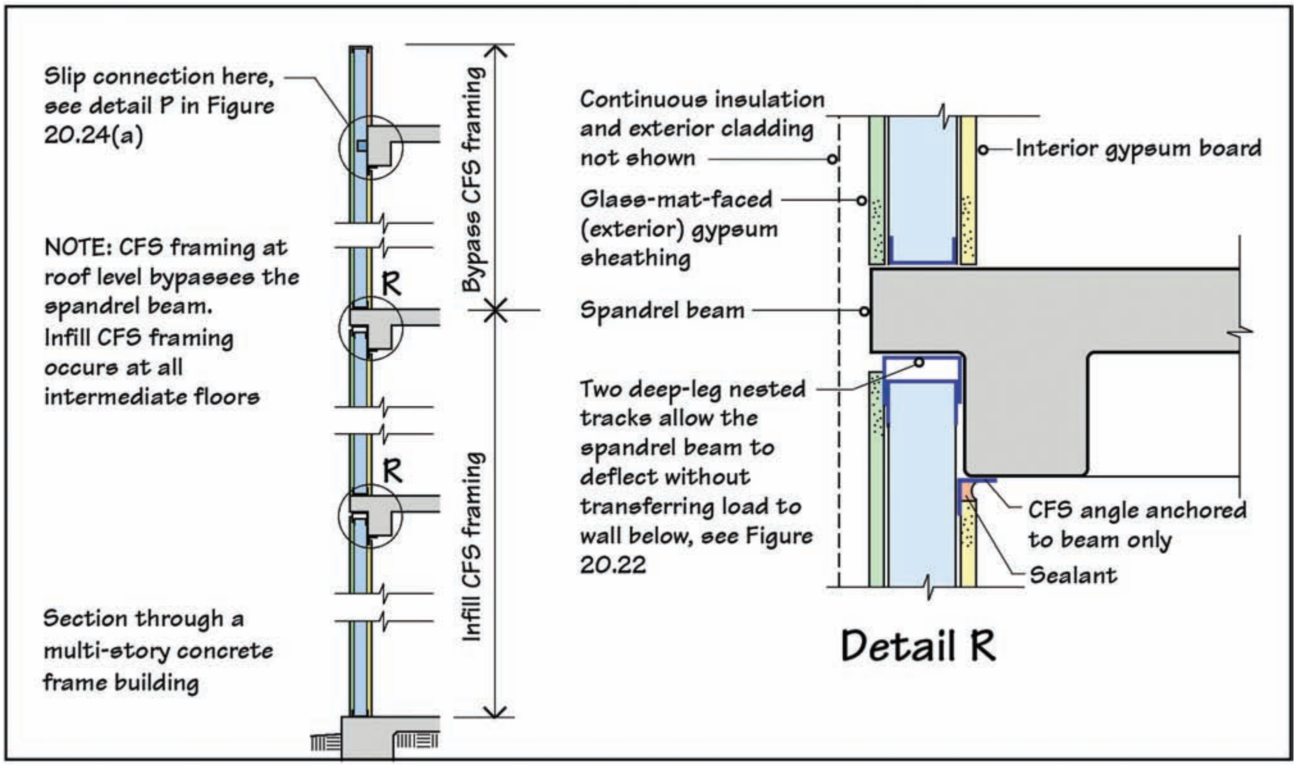

Slip connection here, see detail P in Figure 20.24(a)
NOTE: CFS framing at roof level bypasses the spandrel beam. Infill CFS framing occurs at all intermediate floors
Section through a multi-story concrete frame building
R
R
Bypass CFS framing
Infill CFS framing
Continuous insulation and exterior cladding not shown
Glass-mat-faced (exterior) gypsum sheathing
Spandrel beam
Two deep-leg nested tracks allow the spandrel beam to deflect without transferring load to wall below, see Figure 20.22
Interior gypsum board
CFS angle anchored to beam only
Sealant
Detail R

FIGURE 20.25 Exterior non-load-bearing CFS wall framing for a building of two or more stories.

Buildings With Two or More Stories: The studs extend from floor to floor, Figure 20.25. The exterior framing is brought forward of the structural frame in order to insulate the structural frame. The live deflection of floors is accommodated using a single deep-leg track or two nested deep-leg tracks.

The preliminary size, spacing, gauge, and yield strength of studs are determined in the same way as for the studs in interior partitions, that is, from the tables provided by the individual manufacturers or the industry (e.g., SSMA). The final design must be based on an engineered solution. Most designers use a commercial software for the purpose.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

17. The EQ studs
- **a.** use less steel.
- **b.** are more fire resistive.
- **c.** provide greater sound insulation.
- **d.** all of the above.
- **e.** (a) and (b).

18. The strength of sheet steel used for making EQ studs is
- **a.** 33 ksi.
- **b.** 40 ksi.
- **c.** 50 ksi.
- **d.** greater than 50 ksi.
- **e.** less than 33 ksi.

19. CFS framing for interior gypsum board partitions is designed for a minimum gravity load of
- **a.** 5 psf.
- **b.** 15 psf.
- **c.** 25 psf.
- **d.** 35 psf.
- **e.** none of the above.

20. CFS framing for interior gypsum board partitions is designed for a minimum lateral load of
- **a.** 5 psf.
- **b.** 15 psf.
- **c.** 25 psf.
- **d.** 35 psf.
- **e.** none of the above.

21. CFS framing for interior gypsum board partitions is designed
- **a.** to a maximum permissible deflection of L/120.
- **b.** to a maximum permissible deflection of L/180.
- **c.** to a maximum permissible deflection of L/240.
- **d.** to a maximum permissible deflection of L/300.
- **e.** as needed.

22. In designing CFS interior gypsum board partitions, we can assume either a composite structural behavior or a noncomposite structural behavior. Of the two, noncomposite behavior is more conservative because it ignores the structural contribution of the
- **a.** studs.
- **b.** top track.
- **c.** bottom track.
- **d.** gypsum board.
- **e.** all of the above.

23. If the gypsum board in a CFS interior partition extends the full height of the partition (i.e., from top track to bottom track) on both sides,
- **a.** the assumption of a composite structural behavior is valid.
- **b.** the assumption of a noncomposite structural behavior is valid.
- **c.** any one of the two (composite or noncomposite behavior) is valid depending on the center-to-center spacing of studs.
- **d.** any one of the two (composite or noncomposite behavior) is valid depending on the thickness of the gypsum board.

24. If the gypsum board in a CFS interior partition extends the full height of the partition (i.e., from top track to bottom track) on both sides, the partition is considered as
- **a.** fully braced.
- **b.** braced 12 in. on center if the stud spacing is 12 in.
- **c.** braced 16 in. on center if the stud spacing is 16 in.
- **d.** braced 24 in. on center if the stud spacing is 24 in.
- **e.** unbraced.

25. When bridging channels are required in an interior gypsum board partition, they must be spaced a maximum of
a. 12 in. on center. **b.** 24 in. on center.
c. 36 in. on center. **d.** 48 in. on center.
e. 60 in. on center.

26. The use of two nested top tracks in the framing of an interior gypsum board partition
a. provides greater bending strength in the wall.
b. provides greater shear strength in the wall.
c. provides greater fire resistance in the wall.
d. absorbs the deflection of the overhead structure.
e. seals the partition against the passage of smoke.

27. The CFS framing for an exterior non-load-bearing wall used as backup for exterior cladding can either be a bypass framing or an infill framing. The bypass framing can be used for
a. up to a one-story building. **b.** up to a two-story building.
c. up to a three-story building. **d.** up to a four-story building.
e. up to any number of stories.

28. The CFS framing for an exterior non-load-bearing wall used as backup for exterior cladding can either be a bypass framing or an infill framing. In bypass framing, the studs are connected to an intermediate floor or roof through
a. a clip angle. **b.** a slide clip.
c. an overhanging clip. **d.** two clip angles.
e. none of the above.

20.8 CFS FRAMING IN LOAD-BEARING APPLICATIONS

In load-bearing applications, CFS framing is used in the entire building, that is, all building assemblies—walls, floors, and roofs—are framed with CFS structural members (see Figure 20.11 for the definition of structural members). Such buildings may be classified into two types:

- CFS buildings as Type V(B) construction
- CFS buildings as Type II(A) construction

In the first category, while the structural framing consists of CFS members, the wall sheathing, floor sheathing, and roof sheathing comprises OSB panels. Because of the combustible sheathing, such buildings are classified as Type V construction, generally constructed to qualify as Type V(B) construction, and are, therefore, limited to a maximum of three stories. This system of construction is commonly used for single-family dwellings and competes with WLF construction described in Chapter 15.

The second category is similar to the first category, except that, in place of OSB floor or roof sheathing, precast concrete slabs or concrete-fill-topped steel floor decks are used. Because all materials in the structural assemblies are noncombustible, buildings in this category qualify as Type II construction, Table 20.2. This system is in common use for mid-rise (up to eight stories) apartment and hotel buildings, generally constructed to qualify as Type II(A) construction, Figures 20.26 and 20.27.

The description in the remainder of this chapter covers only the first category—Type V(B) construction—for which CFS framing is an alternative to commonly used wood light-frame (WLF) construction in one- or two-family dwellings.

20.9 CFS BUILDINGS AS TYPE V(B) CONSTRUCTION

The framing details of this system are almost identical to those of the WLF system. A one-for-one equivalence generally exists between WLF and CFS framing details, and there is no

TABLE 20.2 BUILDINGS WITH LOAD–BEARING CFS WALLS, CFS FLOOR AND ROOF FRAMING, AND THEIR TYPES OF CONSTRUCTION

Type of construction	Walls	Floors	Roof
Type V construction, typically Type V(B)	CFS stud and track framing	OSB sheathing on CFS joists	CFS rafters, OSB sheathing, and roof shingles; insulation in attic
Type II construction, typically Type II(A)	CFS stud and track framing	CFS joists with concrete topping OR Precast concrete planks/hollow–core slabs directly on CFS walls	CFS joists, CFS deck, rigid insulation and low-slope roof membrane OR CFS rafters, CFS deck, OSB panels, and roof shingles; insulation in attic

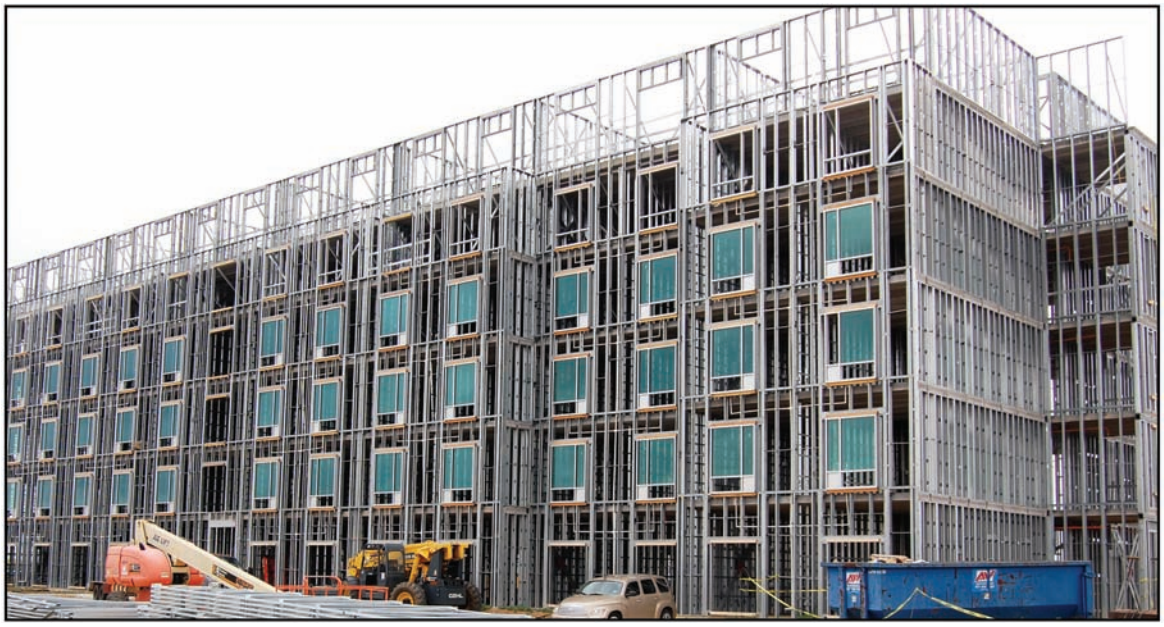


FIGURE 20.26 CFS framing for a six-story load-bearing wall building in progress. In this building the framing of walls, floors, and roof is of CFS members.

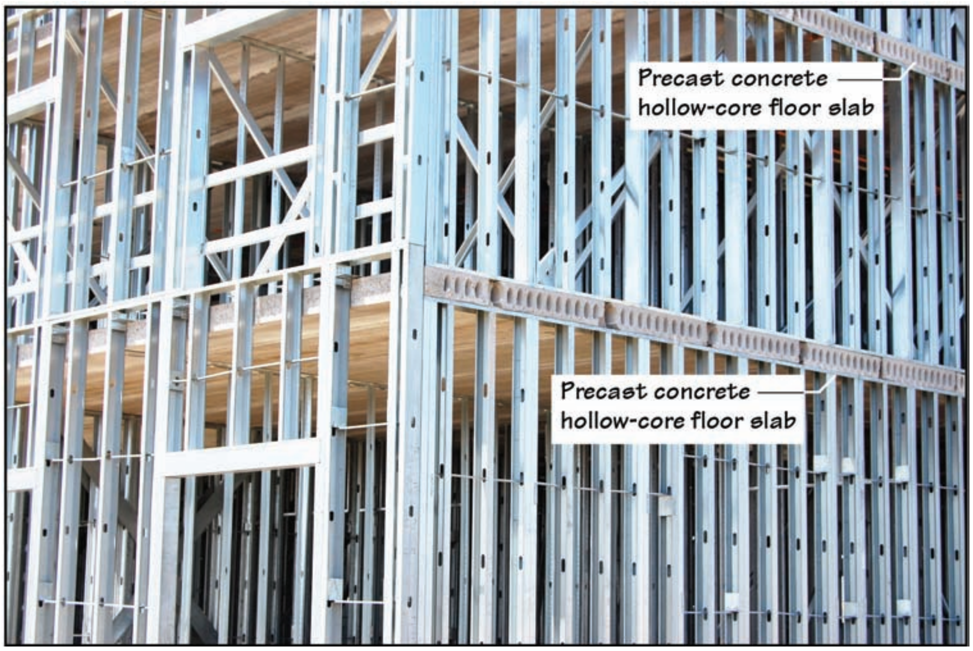

Precast concrete hollow-core floor slab
Precast concrete hollow-core floor slab

FIGURE 20.27 Close-up of the building of Figure 20.26 showing precast concrete hollow-core floor slabs supported on CFS framed walls.

difference in sheathing materials, exterior and interior finishes, HVAC, plumbing, and utility items.

A major difference between the two systems, however, lies in the method of construction. While a WLF building is almost fully constructed at the site (with prefabrication only in roof trusses, where used), CFS wall, floor, and roof assemblies are fabricated off-site and transported to the site as preassembled units, Figure 20.28. The screws used in assembling cold-formed steel members are *self-drilling*, *self-tapping* screws. Self-drilling implies that the screws drill their own holes, and self-tapping implies that they form (i.e., *tap*) their own thread.

CORROSION PROTECTION AND YIELD STRENGTH OF LOAD-BEARING CFS MEMBERS

As shown in Figure 20.11, the minimum corrosion protection required on all CFS members in load-bearing assemblies is CP60. The corresponding yield strength of steel for CFS members is 33 ksi or 50 ksi, as required.

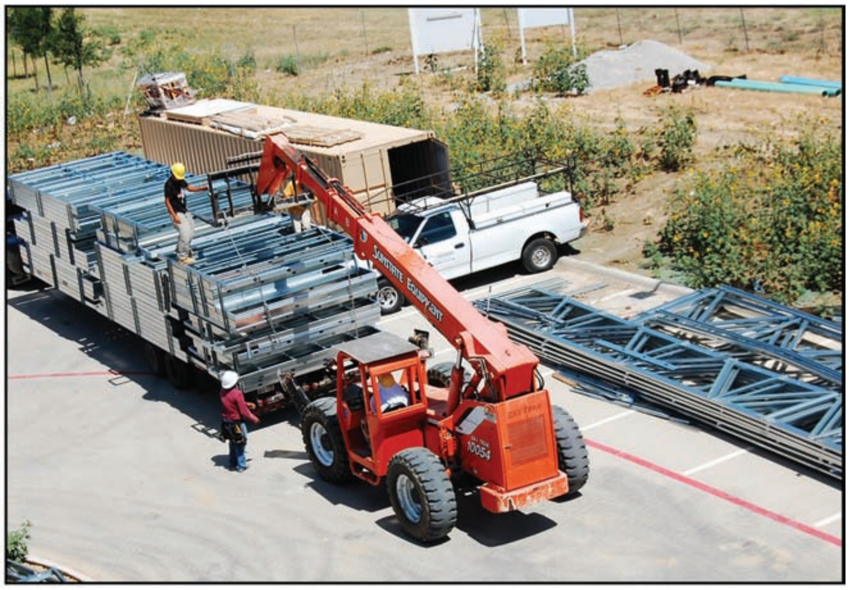


FIGURE 20.28 A forklift is unloading prefabricated CFS assemblies from the truck. CSF walls, floors, and roof assemblies are generally prefabricated off-site into units, and brought to the site for installation and connections.

CFS Load-Bearing Wall Framing

The size of studs commonly used in exterior walls of a typical single-family residence is generally 350S162 or 550S162, with a sheet thickness of 33, 43, 54, or 68 mil (i.e., gauges 20, 18, 16, or 14), depending on the loads and strength of steel. The center-to-center spacing of studs may be 12 in., 16 in., or 24 in. However, because of the steel's higher strength, 24-in. spacing is more common.

Figures 20.29 to 20.31 provide a few important details of wall framing and connections between members showing the similarities and differences between CFS framing and wood framing. An important similarity between the two framing systems is shown in Figure 20.31 with lapped top tracks at a wall corner versus lapped top plates of Figure 15.7. An important difference is highlighted in solid blocking detail of Figure 20.32 which shows that bridging channels cannot be used to prevent rotation of studs in load-bearing walls. Note that the details given here are generic. Manufacturer's details should be referenced for more specific information.

CFS Floor Framing Using In-Line Framing

Figure 20.33 shows the framing of a typical CFS floor. A major difference between a CFS floor and a WLF floor is that CFS floor joists must align with the underlying studs, referred to as *in-line framing*. This is because the commonly used top track in a CFS wall is unable to function as a bending member, unlike the double top plate in a WLF wall.

In-line framing also applies to rafters and roof trusses, so that the load from the floor or roof is transferred directly to the studs. A maximum tolerance of $\frac{3}{4}$ in. between the centerlines of studs and joists or rafters is permitted.

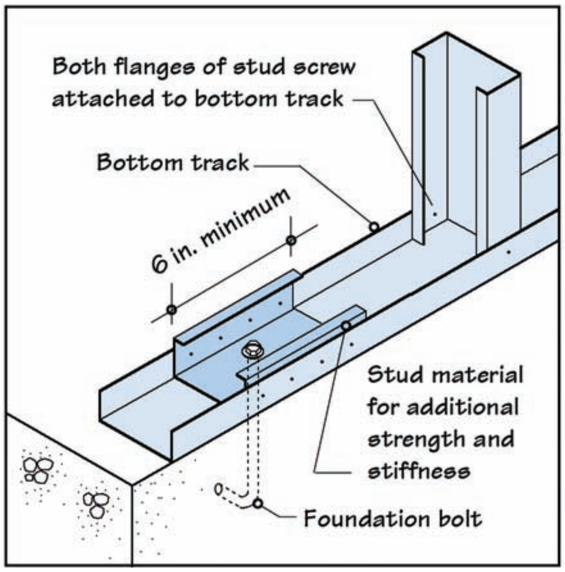

Both flanges of stud screw attached to bottom track
Bottom track
6 in. minimum
Stud material for additional strength and stiffness
Foundation bolt

FIGURE 20.29 Typical detail of the anchorage of CFS bottom track to foundation.

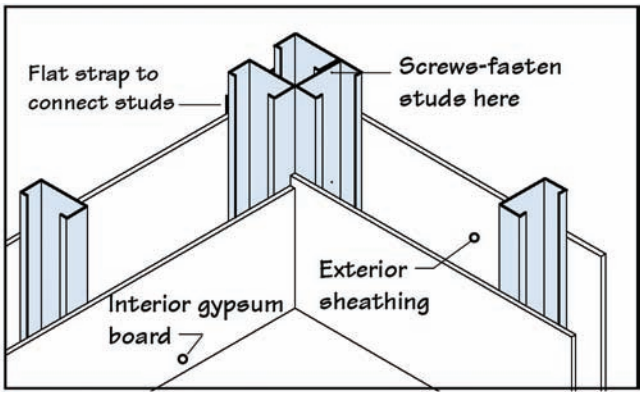


FIGURE 20.30 Configuration of studs at a CSF wall corner. Note that a minimum of three studs are required at a corner, as in a wood light-frame wall. A flat strap is used to connect studs. In a wood light-frame wall, 2-by lumber blocking is used between studs for the connection (see Chapter 15, Figure 15.12).

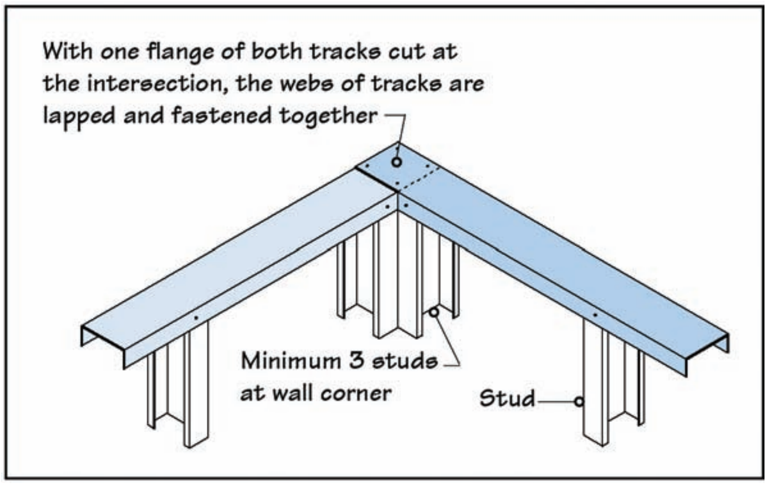

With one flange of both tracks cut at the intersection, the webs of tracks are lapped and fastened together
Minimum 3 studs at wall corner
Stud

FIGURE 20.31 Detail of connection between intersecting tracks at the top of a wall corner.

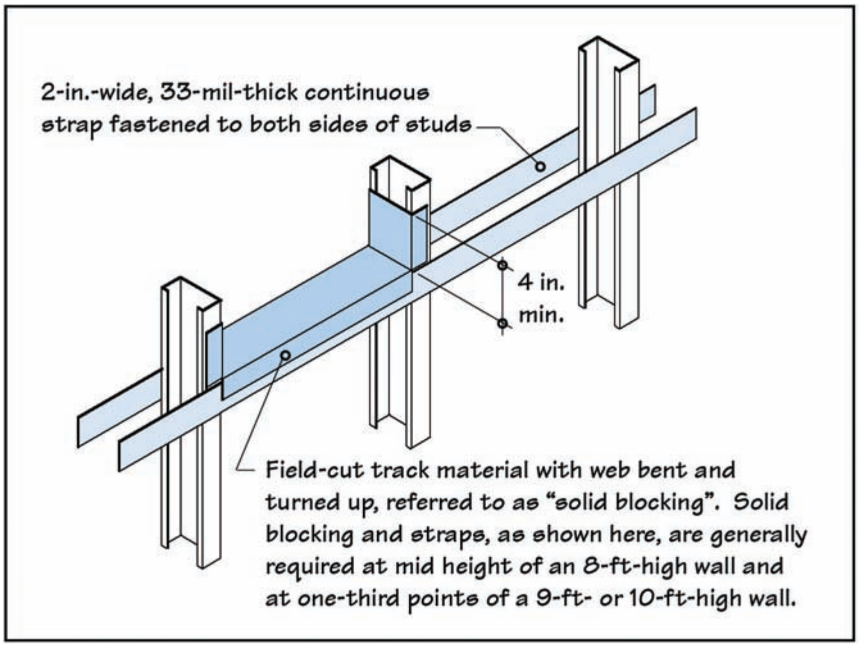

2-in.-wide, 33-mil-thick continuous strap fastened to both sides of studs
4 in. min.
Field-cut track material with web bent and turned up, referred to as "solid blocking". Solid blocking and straps, as shown here, are generally required at mid height of an 8-ft-high wall and at one-third points of a 9-ft- or 10-ft-high wall.

FIGURE 20.32 Blocking of studs to prevent their rotation and buckling under loads. U-channel bridging through punchouts (shown in Figure 20.8) does not provide sufficient bracing for studs in load-bearing applications.

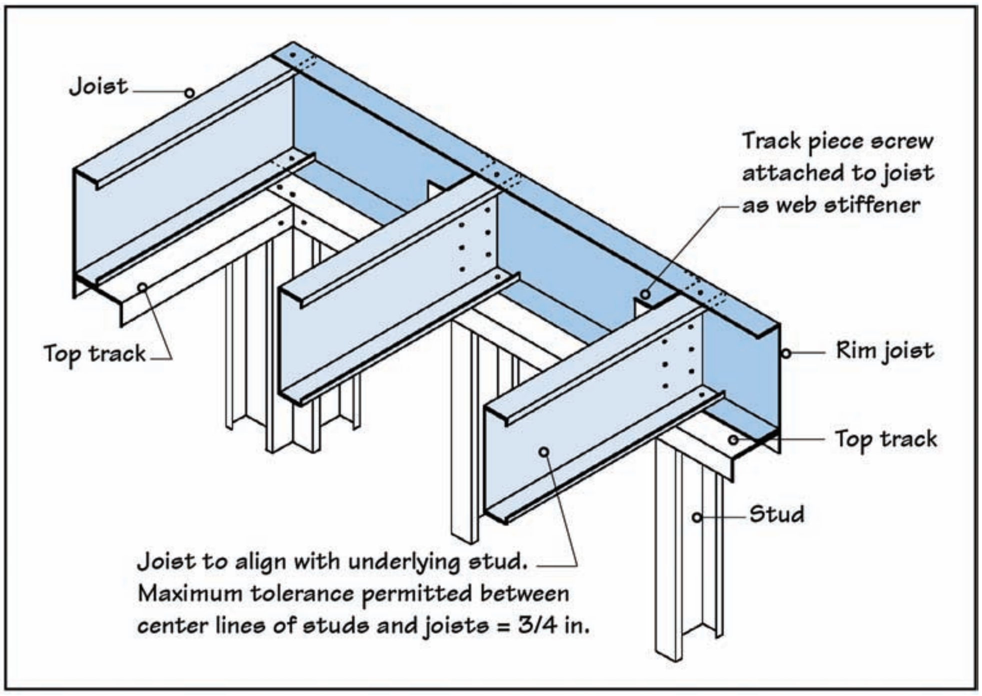

Joist
Track piece screw attached to joist as web stiffener
Top track
Rim joist
Top track
Stud
Joist to align with underlying stud. Maximum tolerance permitted between center lines of studs and joists = 3/4 in.

FIGURE 20.33 Detail showing floor joist supports, web stiffening, and in-line framing of studs and joists.

Joist depths of $7\frac{1}{4}$ in., $9\frac{1}{4}$ in., and $11\frac{1}{4}$ in., which match the depths of standard wood joists, are available in addition to the depths of 8 in., 10 in., 12 in., and 14 in. Once the floor joists are in place, the plywood or OSB subfloor for the next floor is laid in exactly the same way as in a WLF building. After the completion of the subfloor, the walls for the next floor are erected, similar to wood frame construction.

CFS ROOF FRAMING

Because CFS assemblies are prefabricated, roof framing is always in the form of prefabricated trusses. Being lighter than corresponding wood trusses, CFS trusses can generally be hoisted into position with lower-capacity lifting and hoisting equipment. Additionally, the joints between the members of a CFS truss are more rigid, so that the trusses are easier to handle and more forgiving during their placement. In many buildings, roof trusses and the roof deck are assembled into a unit at the construction site, and the unit hoisted into position. Such a unit is far more rigid than the one without the deck. A typical roof detail at the eave is shown in Figure 20.34.

NOTE

In-Line Framing

In-line framing is mandated if the structure is designed using the prescriptive provisions of the building code. Where in-line framing is not to be used, the top track must be engineered.

20.10 THERMAL PERFORMANCE OF CFS WALL ASSEMBLIES

As stated in Chapter 5, the effective R-value of a CFS wall with fiberglass insulation between studs (cavity insulation) is much lower than the R-value of the insulation because of thermal bridging that takes place through studs. Studies have shown that the effective R-value of a CFS wall is a function of: (a) the depth of studs, (b) center-to-center spacing of studs, and (c) the R-value of cavity insulation. Figure 20.35 gives the effective R-values of CFS wall framing with cavity insulation.

If the insulation efficiency is measured by the effective R-value of the assembly (comprising CFS framing plus cavity insulation) divided by the R-value of the cavity insulation, we see that the insulation efficiency decreases as the R-value of cavity insulation increases. For example in Figure 20.35, the effective R-value of the assembly is 6.0 for a wall with $3\frac{1}{2}$-in. studs at 16 in. o.c. and R-13 cavity insulation. Therefore, the insulation efficiency $= \dfrac{6.0}{13.0} = 0.46 = 46\%$.

In other words, 54% of insulation's R-value has been depleted through thermal bridging. For an assembly with 8-in. studs at 16 in. o.c. and R-25 cavity insulation, the effective R-value is 7.8, giving an insulation efficiency of $\dfrac{7.8}{25.0} = 0.31 = 31\%$.

Note that the effective R-values given in Figure 20.35 are for CFS framing plus cavity insulation—without any interior drywall, exterior sheathing panels, or any other item. The total R-value or U-value of a CFS assembly with drywall, sheathing, etc., can be obtained using the procedure given in Chapter 5 (Example 5.3), and as illustrated in Example 20.2.

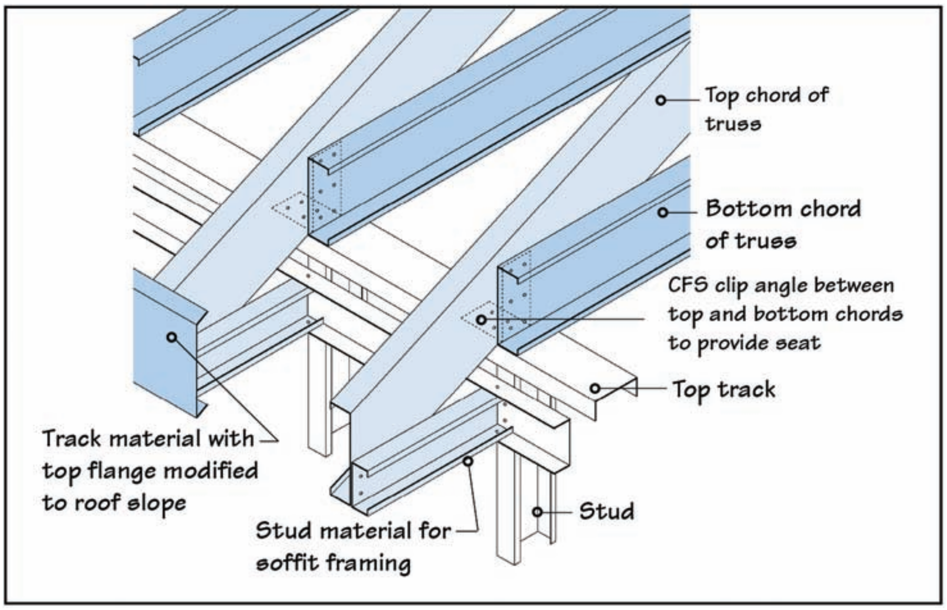

Top chord of truss
Bottom chord of truss
CFS clip angle between top and bottom chords to provide seat
Top track
Track material with top flange modified to roof slope
Stud
Stud material for soffit framing

FIGURE 20.34 A typical eave detail in a CFS roof.

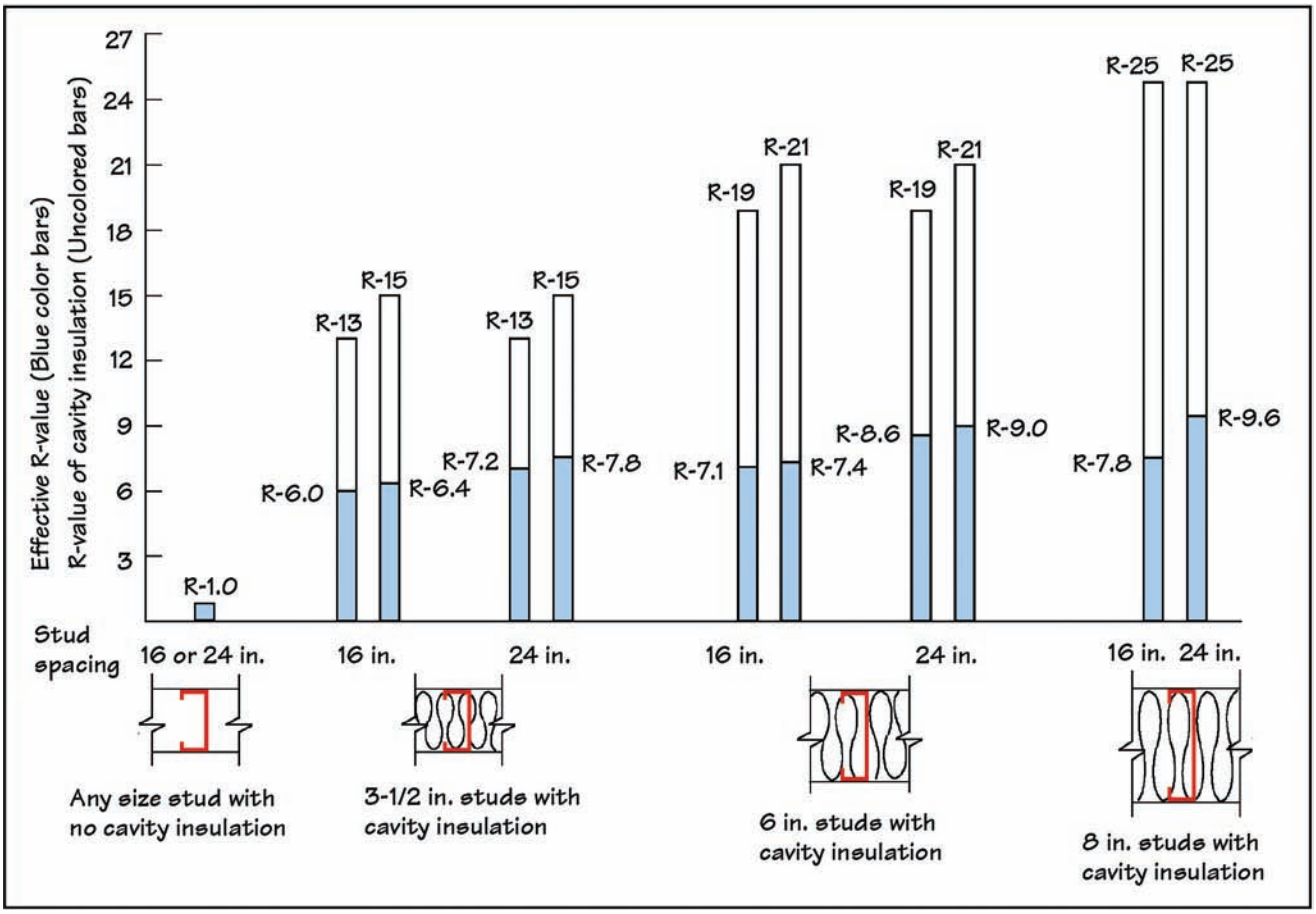


FIGURE 20.35 Effective R-values of CFS wall framing with fiberglass insulation between studs, referred to as cavity insulation [Refs. 20.8 and 20.9]. Cavity insulation has been shown at the top of each bar. The blue-color bar shows the effective R-value of framing-insulation assembly, which does not include the R-value contribution of interior gypsum board, exterior sheathing, interior and exterior surface resistances, etc., see Chapter 5. Note that the effective R-value is approximately 50% of cavity insulation for 3-1/2-in.-deep studs, reducing to approximately 30% of cavity insulation for 8-in.-deep studs.

Example 20.2

The exterior wall assembly, shown in plan in Figure 20.36, is commonly used for commercial buildings. Calculate the assembly's U-value. The cavity insulation is R-13. For R-values of other materials, see Table 5.2. For calculation layout format, follow Example 5.3 in Chapter 5.

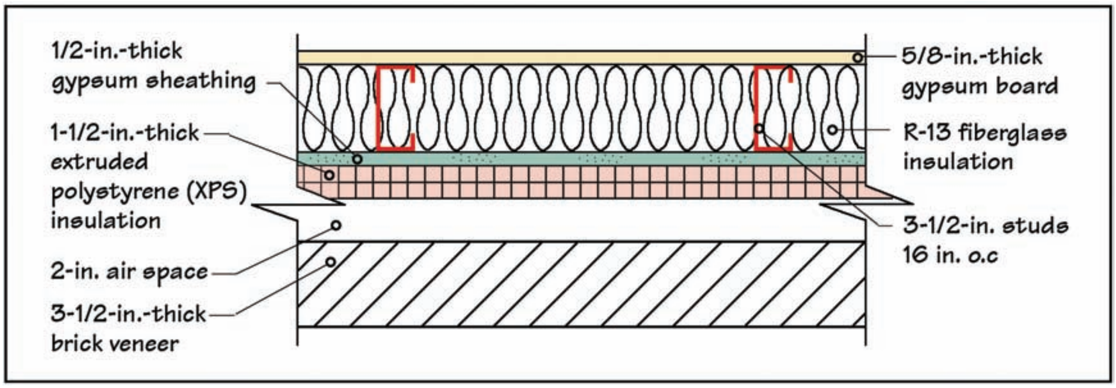

1/2-in.-thick gypsum sheathing
1-1/2-in.-thick extruded polystyrene (XPS) insulation
2-in. air space
3-1/2-in.-thick brick veneer
5/8-in.-thick gypsum board
R-13 fiberglass insulation
3-1/2-in. studs 16 in. o.c

FIGURE 20.36 Exterior wall assembly, refers to Example 20.2.

Solution

From Figure 20.35, the effective R-value of R-13 cavity insulation in a CFS wall = 6.0. The R-values of various layers of the assembly of Figure 20.36 are tabulated below.

Element	R-value
Inside surface resistance	0.7
$\frac{5}{8}$-in.-thick gypsum board	$0.625(0.9) = 0.56$
Stud-fiberglass insulation layer	6.0
$\frac{1}{2}$-in.-thick gypsum sheathing	$0.5(0.9) = 0.45$
$1\frac{1}{2}$-in-thick XPS insulation	$1.5(5.0) = 7.5$
2-in.-wide air space	1.0
$3\frac{5}{8}$-in.-thick brick veneer	$3.625(0.2) = 0.73$
Outside surface resistance	0.2

$$R_t = 0.7 + 0.56 + 6.0 + 0.45 + 7.5 + 1.0 + 0.73 + 0.2 = 17.14$$

$$\text{U-factor of assembly} = \frac{1}{R_t} = \frac{1}{17.14} = 0.583$$

20.11 MAKING OF CFS MEMBERS

CFS steel sections are made by bending coils of galvanized steel sheets at room temperature, in contrast to structural steel sections that are made by rolling billets, slabs, or blooms of steel at temperatures of approximately 2,000°F. CFS manufacturers buy pre-galvanized (or pre-galv-annealed) sheet steel coils, as required. A typical CFS manufacturer has a large area devoted to the storage of sheet steel coils (rolls)—the raw material for CFS members' manufacturing—Figure 20.37.

The process of forming CFS members is conceptually simple. It involves unrolling a sheet steel coil from one end and feeding it into the roll-forming machine, which delivers the bent shape at the other end, Figure 20.38. Because of the simplicity of roll-forming process, several CFS fabricators who assemble CFS members into walls, floors, and trusses (as shown in Figure 20.30) have their own roll-forming machines.

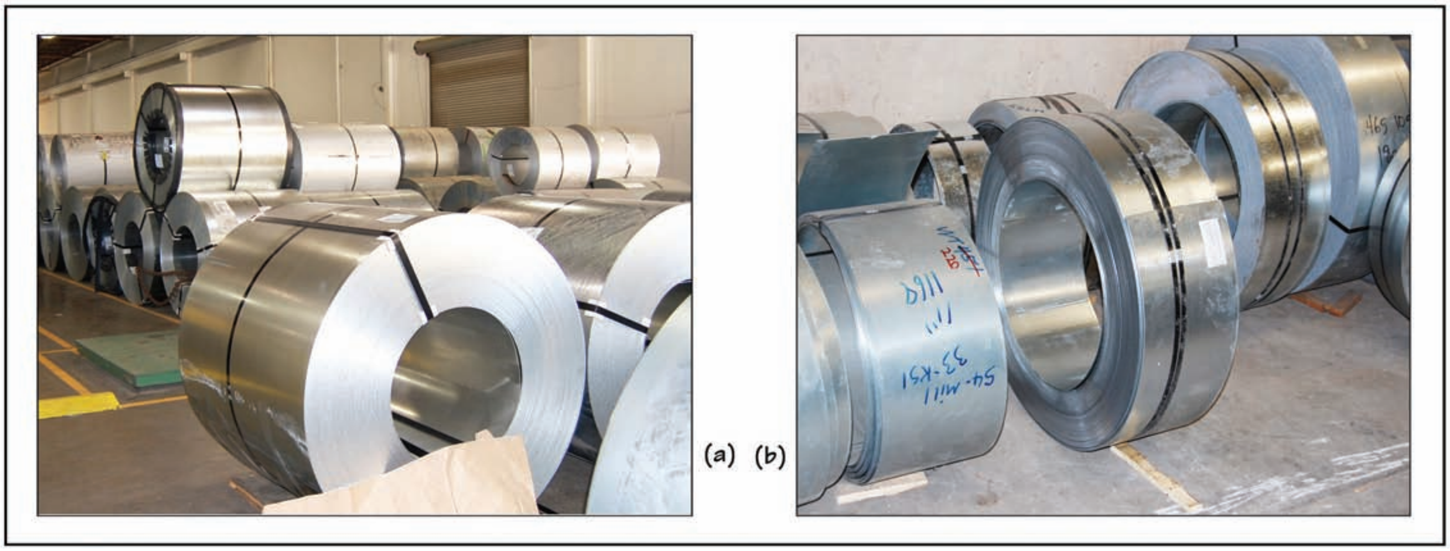


FIGURE 20.37 CFS manufacturers buy coils (rolls) of galvanized sheet steel from sheet steel manufacturers in large widths as shown in **(a)**, which are slit into smaller-width rolls as needed for a particular section, shown in **(b)**. Small CFS manufacturers may not have the machinery needed to convert large-width rolls to smaller-width rolls. So, they buy the rolls as needed.

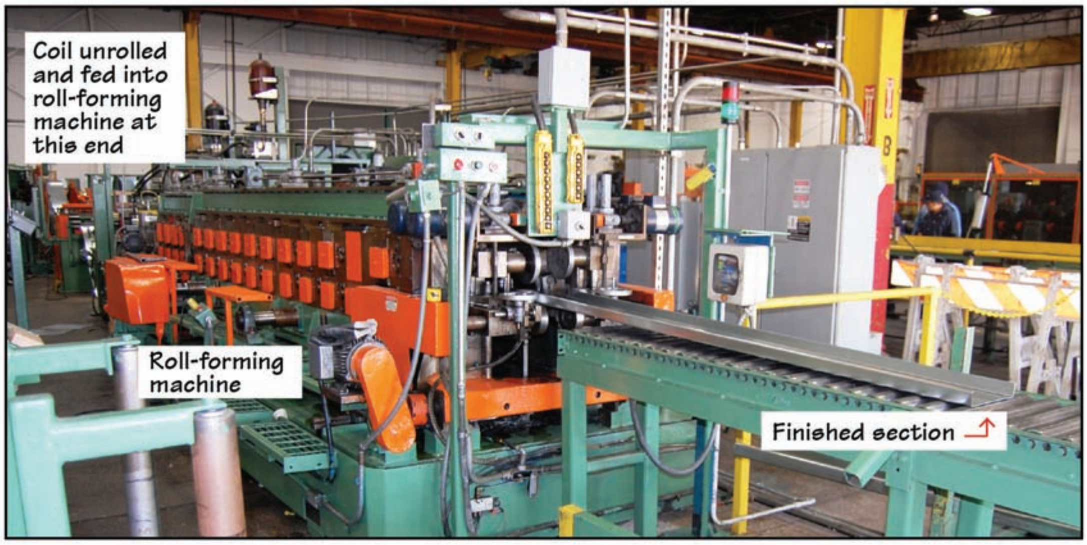


FIGURE 20.38 CFS coil (roll) is unrolled from one end and fed into the roll-forming machine and out comes the required section. In this image, the roll is fed from the left end and the finished section emerges at the right end.

FOCUS ON SUSTAINABILITY

Sustainability Features of Cold-formed Steel

Absence of Mold and Toxic Preservatives

Because steel is an inorganic material, CFS framing does not allow the growth of mold. Additionally, CFS is termite and decay resistant. This implies that, unlike a wood frame building, a CFS building does not require any toxic preservatives (termicide) in its structural frame that might eventually leach into the soil or end up in landfills and from there go into the environment—air and water.

Additionally, because of its termite resistance, the structural frame of a CFS building will remain intact even if the (preconstruction) chemical barrier around the building's foundations is inadequate or compromised.

Recyclability

CFS members are manufactured from coils of galvanized sheet steel that have a large percentage of recycled content (see Chapter 18 for a discussion of the overall recycling of steel). According to the Steel Recycling Institute (SRI), steel is the most recycled material among the important industrial materials. More steel is recycled than aluminum, paper, glass and plastic combined. Because screw connections are used, virtually all CFS members can be easily disassembled after the building's useful life. They may be reused, and, if not, they are 100% recyclable.

SRI website: www.recycle-steel.org

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

29. Two types of buildings with load-bearing CFS walls have been identified in this text: (a) CFS buildings as Type V(B) construction and (b) CFS buildings as Type II(A) construction. The distinction between the two is primarily based on the
- **a.** type of materials used in floor and roof assemblies.
- **b.** size of CFS studs.
- **c.** corrosion protection of CFS members.
- **d.** extent of prefabrication used in construction.
- **e.** none of the above.

30. WLF walls, CFS walls are assembled on site on the floor of the building and subsequently tilted up and moved into position.
- **a.** True
- **b.** False

31. The anchorage of the bottom track of a load-bearing CFS wall to the concrete footing
- **a.** requires 6-in.-long stud material to strengthen the connection.
- **b.** requires 6-in.-long additional track material to strengthen the connection.
- **c.** requires a 6-in.-long cold-formed furring section to strengthen the connection.
- **d.** requires no additional strengthening.

32. The corner of a load-bearing CFS wall requires a minimum of
- **a.** five studs.
- **b.** four studs.
- **c.** three studs.
- **d.** two studs.

33. The top track in a load-bearing CFS wall must be doubled in the same way as the top plate in a WLF wall.
- **a.** True
- **b.** False

34. In-line framing in a CFS structure means that
- **a.** the studs must be continuous across an intermediate floor.
- **b.** the floor joists must align with the studs in the underlying supporting wall.
- **c.** the floor joists from two opposite directions of an underlying supporting wall must be in line, not staggered.
- **d.** the floor-to-floor height in a two- or three-story structure must be the same.

35. The benefit of using load-bearing CFS framing instead of load-bearing wood frame in seismic zones is the
- **a.** lighter weight of CFS framing.
- **b.** ductility of steel.
- **c.** greater strength of CFS members.
- **d.** (b) and (c).
- **e.** (a), (b), and (c).

36. CFS members are made from sheet steel that is provided with corrosion protection before it is formed into shape.
- **a.** True
- **b.** False

37. CFS members are made by roll forming of
- **a.** flat sheets.
- **b.** coils of sheet steel.
- **c.** either of the above two types of sheets depending on the type of roll-forming machine.

REVIEW QUESTIONS

1. Explain what each term in the following identification mark of a CFS member means:
   362S162-43 (50) CP60.
2. What is the difference between CFS member that is hot-dip galvanized and a member that is galv-annealed?
3. Sketch in cross section: (a) CFS stud section, (b) CFS track section, (c) CFS hat section, and (d) CFS Z section.
4. Explain what are EQ studs and tracks, and how they differ from the standard studs and tracks.
5. Using sketches and notes, explain the difference between composite and noncomposite structural behavior with respect to CFS framing for drywall partitions.
6. **a.** What is the minimum lateral load for which an interior drywall partition is designed?
   b. What is the maximum permissible deflection (in inches) of an interior drywall partition which is 12 ft high?
   c. What is meant by a fully braced drywall partition? Explain using sketches.
7. Using sketches and notes, explain what bridging channels are, and where they are required and their maximum center-to-center spacing.
8. Sketch a typical head-of-wall detail for a non-fire-rated interior drywall partition under a reinforced concrete floor slab.
9. Sketch a typical head-of-wall detail for a non-fire-rated interior drywall partition under a steel floor deck. The partition is parallel to deck flutes.
10. Using sketches and notes, explain what is meant by bypass framing and infill framing with respect to CFS backup wall framing for exterior cladding. In which situation(s), is each framing used?
11. Draw the plan of the following wall assembly and then determine its U-value. Starting from the inside face, the assembly consists of: $\frac{1}{2}$ -in. gypsum board, 6 in. studs at 16-in. o.c. with R-21 fiberglass insulation, $\frac{1}{2}$ -in. gypsum sheathing, 2-in. air space, 3 $\frac{5}{8}$-in. brick veneer. (Note: you will need the use of Figure 20.35 and Table 5.2).
12. Draw the plan of the following wall assembly and then determine its U-value. Starting from the inside face, the assembly consists of: $\frac{1}{2}$ -in. gypsum board, 6-in. studs at 16-in. o.c. with no cavity insulation, $\frac{1}{2}$ -in. gypsum sheathing, 3-in.-thick EPS insulation and $\frac{1}{8}$-in.-thick EIFS lamina. (Note: you will need the use of Figure 20.35 and Table 5.2).

CHAPTER 21

Lime, Portland Cement, and Concrete

CHAPTER OUTLINE

21.1 Introduction to Lime
21.2 Types of Lime Used in Construction
21.3 Portland Cement
21.4 Air-Entrained and White Portland Cements
21.5 Basic Ingredients of Concrete
21.6 Important Properties of Concrete
21.7 Making Concrete
21.8 Placing and Finishing Concrete
21.9 Portland Cement and Water Reaction
21.10 Water-Reducing Concrete Admixtures
21.11 High-Strength Concrete
21.12 Steel Reinforcement
21.13 Welded Wire Reinforcement (WWR)

This chapter begins with a discussion of lime, which, until the mid-nineteenth century, was the only cement available for use in masonry mortar, plaster, and concrete. Today, the use of lime is limited to modest quantities in mortar, stucco, whitewash, and soil stabilization.

Portland cement, whose discovery led to the replacement of lime in most applications, is covered next. Without Portland cement, modern architecture, as we know it, would not be possible. In fact, it is virtually impossible to construct a building today without using Portland cement in some form.

Portland cement is the main ingredient in concrete. Therefore, a discussion of concrete follows that of Portland cement. Concrete is covered here as a material. Its applications, that is, concrete construction systems, are discussed in the following two chapters.

Because concrete is generally used in conjunction with steel reinforcement (as reinforced concrete), we also cover steel reinforcement here.

21.1 INTRODUCTION TO LIME

Lime is a cement (binder) and has been used for thousands of years in masonry mortars to bind the stone and brick units in walls. Until the discovery of Portland cement, lime-sand mortar was the only masonry mortar available. Egyptians used lime-sand mortar in the construction of pyramids, and virtually all historic stone buildings in Europe used lime-sand mortar. In lime-sand mortar, lime is the binder and sand is the filler.

Lime is made from limestone, one of the most abundant rocks in the earth's crust. Chemically, limestone is calcium carbonate. Lime is produced by simply heating limestone—a process known as *calcining*.

Calcining is typically done by first crushing limestone rock into approximately 2-in. particles and then heating them in a kiln to a temperature of approximately 1,800°F (1,000°C). Calcining expels the carbon dioxide from calcium carbonate, leaving calcium oxide. (It is an endothermic reaction, implying that heat is required for the reaction.)

Calcium oxide is called *quicklime*. Quicklime is a caustic substance that corrodes metals and causes severe damage to human skin. However, it reacts readily with water to form calcium hydroxide. Calcium hydroxide is called *hydrated lime*, or *slaked lime*, because it contains water that is chemically combined with calcium oxide. It is a relatively benign material and is the one that is commonly used in building construction.

Both quicklime and hydrated lime are white in color. Hydrated lime is generally used in powder form. The amount of water used to hydrate quicklime is much greater than that required for the hydration reaction. Therefore, after completion of the hydration reaction, the quicklime and water mixture is dried to evaporate the excess water. The dried hydrated lime is then pulverized to powder form. In the United States, hydrated lime is sold in 50-lb bags, Figure 21.1.

NOTE

A Note on Quicklime

Historical records indicate that British soldiers used quicklime to incapacitate their French enemies in the war of 1217 by throwing it in their faces—one of the earliest records of chemical warfare.

The chemical reaction of quicklime with water (hydration reaction) is exothermic, implying that heat is produced during the reaction. The amount of heat produced in the hydration of 1 lb of quicklime is nearly 450 Btu. Because 1 Btu is the amount of heat required to raise the temperature of 1 lb of water by 1°F (Chapter 5), 450 Btu will raise the temperature of 3.2 lb of water from 70°F to 212°F (21 to 100°C)—the boiling point of water. In other words, if 1 lb of quicklime is mixed with 3.2 lb of water initially at room temperature, that water will begin to boil.

Wood box carts carrying quicklime have ignited through accidental penetration of rainwater through leaks in the carts. Criminals misused quicklime to dispose of the corpses of their victims by dumping them in a pit, covering them with quicklime, and backfilling with wet soil.

50 LBS. NET
TEXAS LIME COMPANY
HYDRATED LIME
WARNING
KEEP OUT OF REACH OF CHILDREN
See Back Panel For Caution Before Use
Chemical Quality
TEXAS LIME COMPANY CLEBURNE, TEXAS
TEXAS LIME

FIGURE 21.1 A typical lime bag.

CARBONATION OF LIME

The hardening property of lime results from its ability to react with atmospheric carbon dioxide to form calcium carbonate—the raw material used in making lime. Thus, the chemical reaction of lime with carbon dioxide (carbonation reaction) returns lime to its parent material—limestone—which is hard and strong. Stated differently, the calcination of limestone results in quicklime; the hydration of quicklime produces hydrated lime; and the carbonation of hydrated lime changes it to limestone. These three processes constitute a cycle, Figure 21.2.

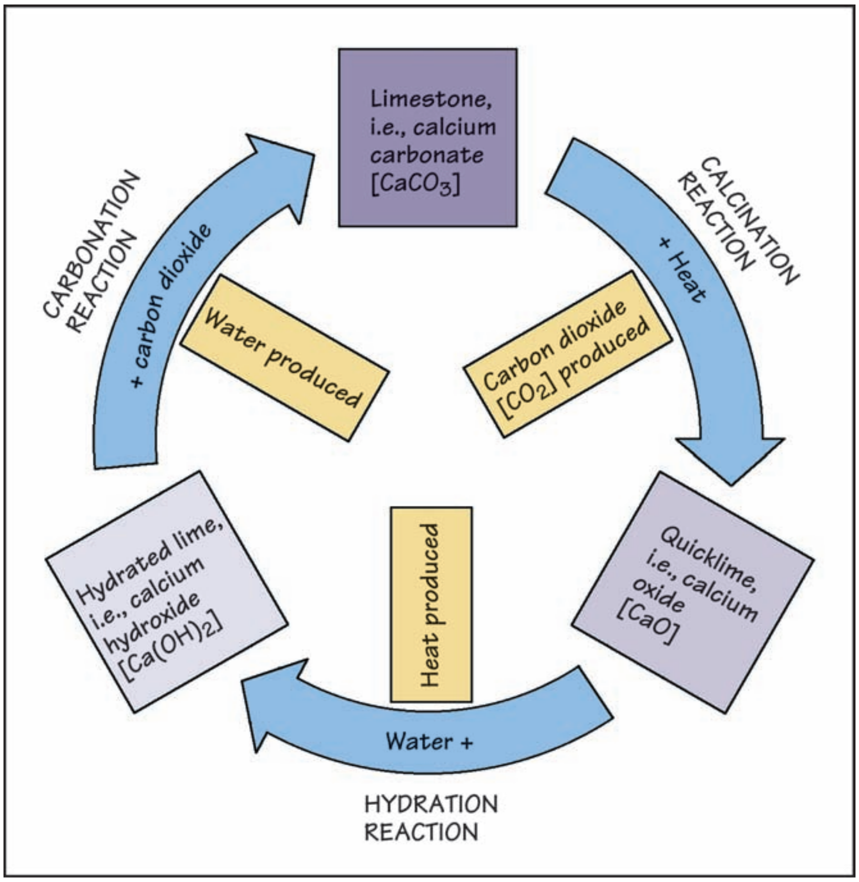

Limestone, i.e., calcium carbonate [$CaCO_3$]
CALCINATION REACTION
+ Heat
Carbon dioxide [CO_2] produced
Quicklime, i.e., calcium oxide [CaO]
Heat produced
Water +
HYDRATION REACTION
Hydrated lime, i.e., calcium hydroxide [$Ca(OH)_2$]
Water produced
CARBONATION REACTION
+ carbon dioxide

FIGURE 21.2 Limestone cycle—calcination, hydration, and carbonation.

NOTE

Chemistry of Lime

Calcination of Limestone

$$\text{Limestone} \xrightarrow{\text{Heat}} \text{lime} + \text{carbon dioxide}$$

$$CaCO_3 \xrightarrow{\text{Heat}} CaO + CO_2$$

Hydration of Quicklime

$$\begin{array}{lcl}\text{Calcium oxide} & \longrightarrow & \text{Calcium hydroxide} \\ +\text{water} & & +\ \text{heat}\end{array}$$

$$CaO + H_2O \longrightarrow Ca(OH)_2 + \text{heat}$$

Carbonation of Hydrated Lime

$$\begin{array}{lcl}\text{Calcium hydroxide} & \longrightarrow & \text{Calcium carbonate} \\ +\text{carbon dioxide} & & +\ \text{water}\end{array}$$

$$Ca(OH)_2 + CO_2 \longrightarrow CaCO_3 + H_2O$$

NOTE

Roman Concrete and Mortar

Historians conjecture that the Romans discovered lime from cooking and heating hearths, which were generally made of limestone slabs. The fire from the hearths calcined the limestone, and subsequent rain showers hydrated it. Volcanic ash was abundantly available in the region because it had a number of active volcanoes at the time.

In fact, the term *pozzolana* is derived from Pozzuoli, a town in southern Italy that had several active volcanoes during the Roman period. Abundant evidence of extinct volcanoes is available on the outskirts of modern Pozzuoli.

As the atmospheric carbon dioxide begins to react with lime-sand mortar in a wall, the exposed areas of the mortar begin to convert into a hard carbonate crust, resulting in the setting and hardening of mortar. This crust hinders further penetration of carbon dioxide into the interior volume of mortar. Therefore, the setting of lime-sand mortar is slow. The slow setting is also due to the fact that only a small fraction (less than 0.04%) of air is carbon dioxide. Thus, it is difficult to lay more than a few masonry courses per day using lime-sand mortar because the weight of additional courses squeezes the mortar out of masonry.

The cementing property of lime is not simply the result of its hardening but is due more to the absorption of water in mortar by brick or stone units. As the water evaporates and the mortar shrinks, it draws the units toward itself. The tiny pores, pits, and crevices on the surfaces of the units, which get filled with fresh mortar, add to lime's cementing property.

POZZOLANIC REACTION—ROMAN CONCRETE AND MORTAR

In addition to its hardening caused by carbonation, lime experiences another type of hardening. This is caused by lime's reaction with amorphous (noncrystalline, i.e., glassy) silica, referred to as a *pozzolanic reaction*. Although not understood scientifically at the time, the pozzolanic reaction was first discovered by ancient Romans around the first or second century BC.

Romans found that if lime and volcanic ash were mixed, the mixture, when used with sand and water, gave a mortar that set more quickly, was stronger, and was more durable than lime-sand mortar. The greater durability was due to the pozzolanic reaction that occurs when lime and volcanic ash are mixed with water. The mixture produces a water-resistant, or *hydraulic cement*—a cement that does not dissolve in water. Lime by itself (i.e., free lime, defined as lime in the absence of the pozzolanic reaction) dissolves slowly in water over a period of time.

The main ingredient of volcanic ash is microscopic silica (with a small percentage of microscopic alumina). As the volcanic lava jets out of the ground, the carbon in the rock and other organic matter are converted to carbon dioxide gas, which carries with it particles of rock that have melted and fused into glassy (amorphous) particles. (Soil and most rocks consist mainly of oxides of silicon and aluminum, called *silica and alumina*, respectively.)

Due to the pressure of volcanic eruption, molten glass particles are converted to tiny beads of glass, which we call *volcanic ash*. It is both the microscopic size and the amorphous nature of silica and alumina in volcanic ash that gives it the pozzolanic property. Therefore, volcanic ash is called a *pozzolanic material* or simply a *pozzolana*.

Ancient Romans perfected the art and science of making hydraulic cement from lime and volcanic ash and used it to produce concrete, known as *Roman concrete*, which is not too different from present-day concrete. Romans used two closely spaced stone or brick walls as the permanent formwork, within which the concrete was placed. In many such buildings, the facing walls have disintegrated or part of the wall has fallen, revealing the interior concrete.

Because their cement was hydraulic, the mortar used in Roman masonry was also hydraulic. The Romans exploited this property to build aqueducts to supply water to the city of Rome, Figure 21.3. Architectural historians claim that the 150-ft-diameter dome of the Pantheon in Rome, built around AD 120 and still standing, is made of concrete using lime, volcanic ash, and broken stone.

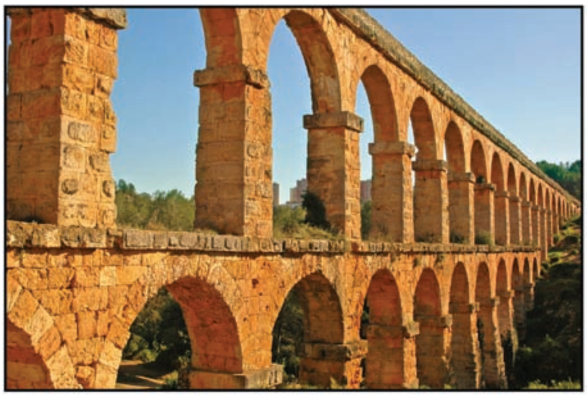


FIGURE 21.3 Pont del Diable Roman aqueduct, Terragona, Spain. (Photo courtesy of Nito/Shutterstock)

21.2 TYPES OF LIME USED IN CONSTRUCTION

The composition of lime outlined previously assumed that limestone consists only of calcium carbonate. This is only partially correct because limestone occurs in two types:

- *High-calcium limestone*, consisting of approximately 95% calcium carbonate
- *Dolomitic-limestone*, consisting of approximately 60% to 80% calcium carbonate (see Section 25.7)

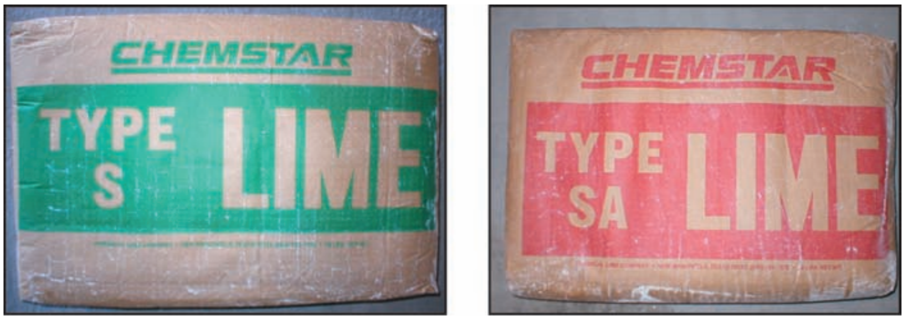


FIGURE 21.4 Type S hydrated lime and Type SA hydrated lime bags.

Dolomitic limestone shares most of its properties with high-calcium limestone; that is, it can be calcined to obtain quicklime. Quicklime obtained from dolomitic limestone is calcium oxide chemically combined with magnesium oxide ($CaO \cdot MgO$). Although dolomitic quicklime also has great affinity for water, it does not hydrate as readily as calcium oxide.

Higher temperature and pressure are generally needed to fully hydrate all magnesium oxide. Unhydrated oxides in lime are problematic (particularly in plaster work) because, given the right temperature, pressure, and humidity, they can hydrate abruptly well after construction is complete. Because the hydration of lime is exothermic, blistering and popping generally occur.

The lime industry produces the following two types of hydrated lime:

- Type N (normal) hydrated lime
- Type S (special) hydrated lime

Type S hydrated lime has maximum (8%) unhydrated oxides. In Type N, there is no such limitation. Type S lime is more expensive and is preferred over Type N lime, not simply because of the limited amount of unhydrated oxides but also because it has greater workability and plasticity.

Lime used in masonry mortar and plastering is generally Type S hydrated lime. Manufacturers label bags of Type S lime, Figure 21.4. A bag that is not labeled is usually Type N lime, as shown in Figure 21.1.

Type S lime can be produced from either dolomitic or high-calcium limestone. In the United States, dolomitic limestone is preferred because it gives greater workability to lime—a quality that masons and plasterers require. Lime is also produced with air-entraining agents mixed with it. Air entrainment increases the resistance of lime mortar against the freeze-thaw effect but decreases its strength (Section 21.4). Air-entrained lime is labeled by manufacturers as NA lime or SA lime.

NOTE

Pozzolana

By definition, a pozzolanic material (also called *pozzolana*) is a material that, when mixed with lime and water, converts the mixture into a hydraulic cement. For it to be a pozzolana, the material must be extremely small (microscopic) in particle size and contain amorphous silica. (See the introduction to Chapter 28 for the meaning of the term *amorphous*.)

A commonly used present-day pozzolana is fly ash—a waste product from coal-fired electricity generating stations. Like volcanic ash, fly ash contains microscopic and amorphous silica and alumina. The average size of particles in fly ash is less than 20 μm [21.1](1 μm, called a *micrometer*, is one-millionth of a meter, or 0.001 mm). By comparison, the average Portland cement particle size is 45 μm = 0.045 mm.

Another contemporary pozzolana is silica fume—a waste product from the silicon industry. The particle size of silica fume is even smaller than that of fly ash (see Section 21.11).

The reaction between lime and a pozzolana yields a complex form of calcium silicate hydrate, which is the main constituent produced when Portland cement is mixed with water. Because Portland cement is a much better hydraulic cement, lime and pozzolanas are not used directly in contemporary construction.

NOTE

Workability and Plasticity

The term *workability* is used with reference to concrete, mortar, and plaster mixes. With concrete, it is somewhat quantified by the slump measure (see Section 21.6). With mortar and plaster mixes, there is no such quantification of workability. However, a good mason can judge workability while spreading the mortar or plaster mix with a trowel.

Basically, a workable mortar or plaster will spread more easily—a difference similar to spreading a crunchy peanut butter or a creamy peanut butter on a piece of toast.

The term *plasticity* is related to workability. It is a measurable term with reference to mortar and plaster mixes. Workability includes *plasticity* and *water retentivity*. A mortar mix with a higher degree of plasticity and water retentivity is a more workable mix. Water retentivity is described in Section 24.1.

USES OF LIME

Lime is used in construction as well as nonconstruction activities. Some of the nonconstruction uses of lime are in water purification, water softening, sewage sludge treatment, manufacturing of plastics and paints, and so on. Lime is used in municipal water-treatment plants because of its disinfecting property. It removes hazardous compounds, such as lead, from water and also softens hard water. In construction activities, lime is principally used in:

- Masonry mortar (Chapter 24)
- Plaster and stucco (Chapter 29)
- Soil stabilization

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. Lime is made by
- **a.** heating crushed limestone and then pulverizing it.
- **b.** mixing crushed limestone with water and then pulverizing the mixture.
- **c.** mixing crushed limestone with sulfuric acid and then pulverizing the mixture.
- **d.** mixing crushed limestone with nitric acid and then pulverizing the mixture.

2. Quicklime reacts readily with water.
- **a.** True
- **b.** False

3. Hydrated lime is obtained by treating
- **a.** slaked lime with water.
- **b.** quicklime with water.
- **c.** limestone with water.
- **d.** slaked lime with Portland cement.
- **e.** quicklime with Portland cement.

4. Quicklime is most commonly used in building construction.
- **a.** True
- **b.** False

5. Hydrated lime–water paste sets and hardens due to the
- **a.** chemical reaction of water with lime.
- **b.** chemical reaction of oxygen in air with lime.
- **c.** chemical reaction of carbon dioxide in air with lime.
- **d.** chemical reaction of nitrogen in air with lime.
- **e.** chemical reaction of water in lime with carbon dioxide in air.

6. Which of the following materials is a pozzolana?
- **a.** Portland cement
- **b.** Lime
- **c.** Fly ash
- **d.** Sand
- **e.** Concrete

7. One of the important cementitious ingredients in making Roman concrete was
- **a.** clay.
- **b.** volcanic ash.
- **c.** sand.
- **d.** Portland cement.
- **e.** none of the above.

8. Hydrated lime is available in two types, which are referred to as
- **a.** Types N and S lime.
- **b.** Types I and II lime.
- **c.** Types X and Y lime.
- **d.** Types A and B lime.
- **e.** Types 1 and 2 lime.

9. A pozzolanic material must be composed mainly of
- **a.** microscopic silica.
- **b.** microscopic and amorphous silica.
- **c.** microscopic and crystalline silica.
- **d.** silica and alumina.
- **e.** amorphous silica and alumina.

21.3 PORTLAND CEMENT

Portland cement, a hydraulic cement, was patented in 1824 by Joseph Aspidin, a British stonemason. Aspidin burned finely ground limestone and clay in a kiln and found that the resulting product was a hydraulic cement, which set and gained strength much more quickly than lime.

Aspidin called his new product *Portland cement* because the concrete that he made from it resembled, in color and strength, a highly sought-after natural limestone quarried from the Isle of Portland, off the British coast. Note that Portland cement is no longer a brand name but a generic one; therefore, a large number of manufacturers produce Portland cement.

Modern Portland cement is made from almost the same basic raw materials and virtually by the same basic process that Aspidin used, that is, by heating a mixture of limestone and clay. Limestone comprises approximately two-thirds of the raw material required for making Portland cement.

Another major raw material required is clay or shale. (Shale is a highly compressed form of clay.) Clay consists of the oxides of silicon, aluminum, and iron—called *silica, alumina*, and *iron oxide*, respectively. Some clays can provide all the silica, alumina, and iron oxide required in the manufacture of Portland cement. Other clays may be supplemented by sand (to provide silica), bauxite (to provide alumina), and iron ore (to provide iron oxide). Generally, therefore, one or two raw materials, in addition to limestone and clay, are needed in Portland cement's manufacture.

MANUFACTURING PROCESS OF PORTLAND CEMENT

The manufacture of Portland cement begins with quarrying limestone, which is later crushed to approximately $\frac{5}{8}$-in.-size particles. Crushed limestone and other raw materials (clay, sand, and iron ore) are stored in silos for processing as needed. Figure 21.5 is a conceptual diagram of the entire manufacturing process.

The raw materials are mixed together in required proportions and ground to a fine powder in a grinding mill. Powerful fans draw the powder from the grinding mill into a dust collector, and from there it is taken to storage silos. From the silos, the powder goes into a rotating, or rotary, kiln.

The rotary kiln—a huge steel cylinder lined inside with refractory bricks—is at the heart of the manufacturing process. It is considered to be the heaviest rotating industrial equipment. It is slightly sloped to allow the material to tumble forward by gravity, Figure 21.6. The kiln temperature increases as the material moves forward. In the initial section of the kiln, where

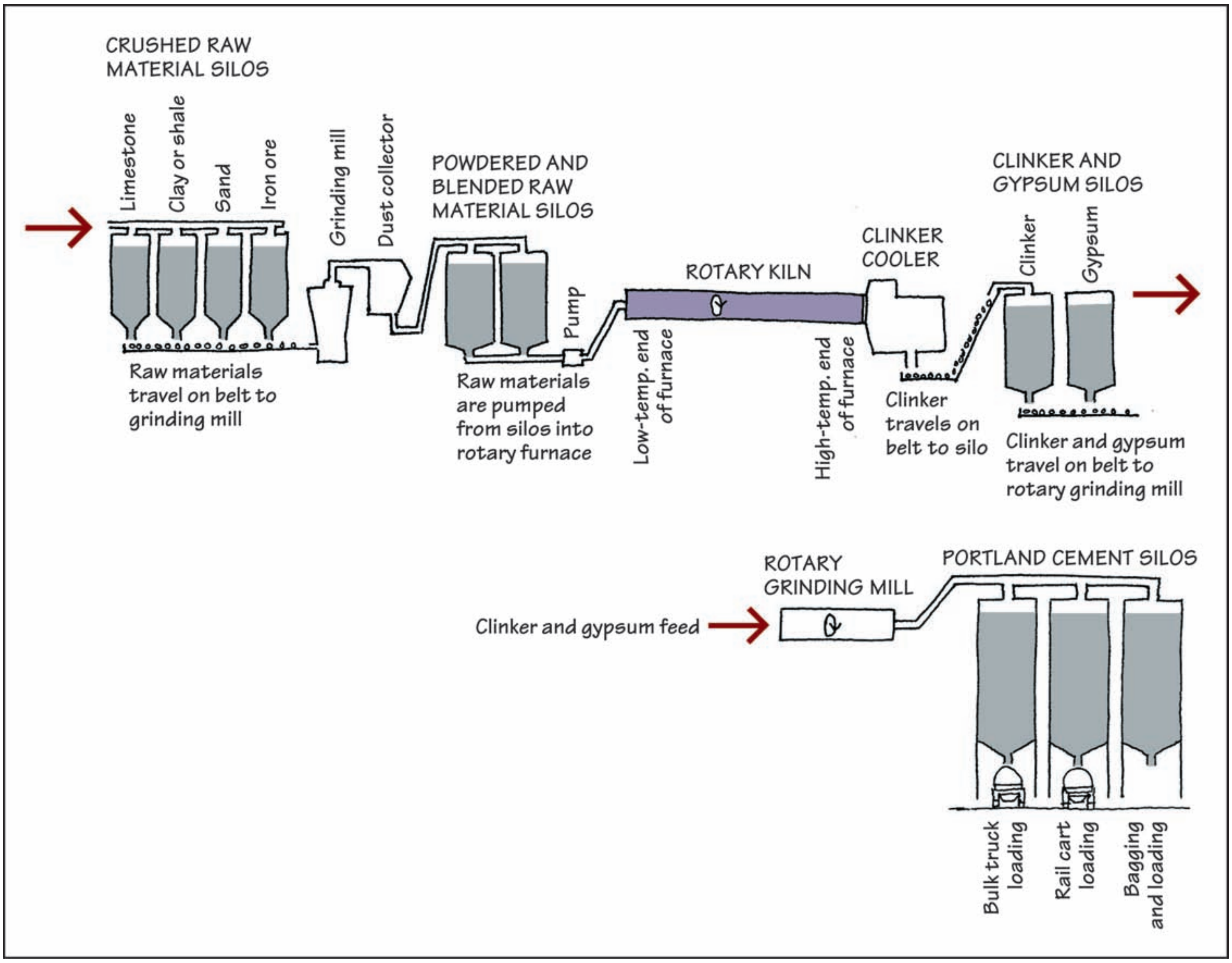

CRUSHED RAW MATERIAL SILOS
Limestone
Clay or shale
Sand
Iron ore
Grinding mill
Dust collector
POWDERED AND BLENDED RAW MATERIAL SILOS
Pump
ROTARY KILN
CLINKER COOLER
CLINKER AND GYPSUM SILOS
Clinker
Gypsum
Raw materials travel on belt to grinding mill
Raw materials are pumped from silos into rotary furnace
Low-temp. end of furnace
High-temp. end of furnace
Clinker travels on belt to silo
Clinker and gypsum travel on belt to rotary grinding mill
ROTARY GRINDING MILL
PORTLAND CEMENT SILOS
Clinker and gypsum feed
Bulk truck loading
Rail cart loading
Bagging and loading

FIGURE 21.5 An outline of the Portland cement manufacturing process.

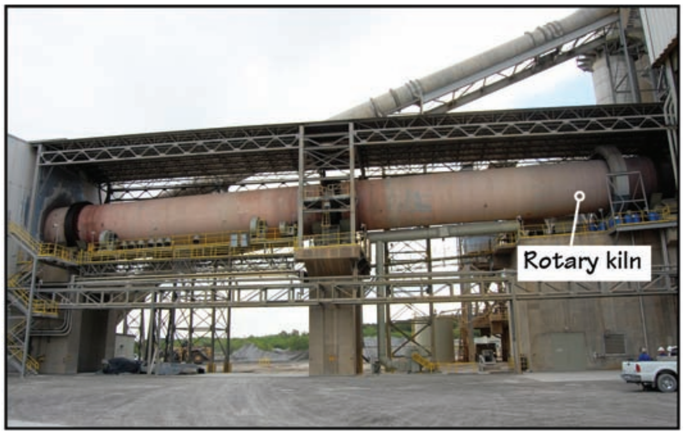

Rotary kiln

FIGURE 21.6 Rotary kiln in the Portland cement manufacturing plant in Midlothian, Texas.

the temperature is around 1,800°F (1,000°C), calcium carbonate is converted to calcium oxide, similar to the manufacturing of lime. The discharge of carbon dioxide is, therefore, a major environmental pollutant in the neighborhood of a Portland cement plant.

Toward the far end, where the temperature reaches approximately 3,400°F (1,900°C), calcium oxide reacts with other raw materials to form complex calcium compounds. Materials become partially molten and coalesce into approximately 1-in.-size nodules called *clinkers*, Figure 21.7. The clinker is cooled and stored in silos.

In the final manufacturing stage, a small quantity of gypsum is added to the clinkers to control the setting properties of Portland cement. Clinkers and gypsum are ground and blended into a very fine powder, which is considered Portland cement. It is then stored in

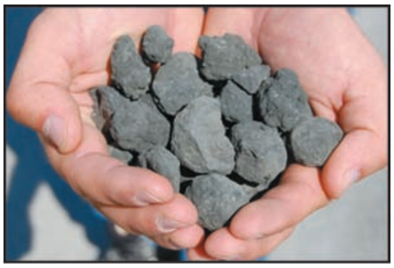


FIGURE 21.7 Clinker size and shape.

silos for transportation in trucks or railroad cars or to a bagging facility. Portland cement is gray in color, with an average particle size of approximately 45 μm.

TYPES OF PORTLAND CEMENT

Most Portland cement is used in making concrete, required for buildings, pavements, roads, bridges, and dams. Other uses of Portland cement are in masonry mortar, plaster, stucco, siding, and flooring. Because the requirements for various concretes and other mixes vary, Portland cement is manufactured in five different types—Types I, II, III, IV, and V. These types are distinguished from each other by small changes in their chemical composition, giving them different properties, Table 21.1.

Type I is a *general-purpose* Portland cement. Type III Portland cement is *high-early-strength* Portland cement. It develops strength at a faster rate than other types in the initial stage, but its final strength is the same as that of the other types. As described in Section 21.9, Portland cement develops its ultimate strength over several months.

Type III Portland cement is generally used in making precast concrete elements, such as hollow-core slabs, double-tees, and concrete pipes. Economic considerations require that the formwork for precast elements be used as frequently as possible. Generally, precast concrete elements are cast one morning and stripped off the form the following morning, giving a 24-h turnover cycle (see Chapter 23).

Type IV is *low-heat-of-hydration* Portland cement. It is meant for use in massive concrete structures (dam walls or bridge piers), where the temperature rise due to heat generated from hydration must be minimized. Due to its limited use, Type IV cement is produced by manufacturers only on special request.

Type V is *sulfate-resistant* Portland cement. Portland cement can be affected adversely by the presence of sulfur. In fact, concrete made out of Type I Portland cement will decompose into small fragments (spall) after just a few years in the presence of high-sulfur-containing environments. Some soils and groundwater have a high sulfur content. The use of Type V Portland cement is recommended in such environments.

Type II is *moderate-sulfate-resistant* and *moderate-heat-of-hydration* Portland cement. It combines the properties of Types IV and V to a moderate degree. Therefore, most manufacturers make Portland cement that meets the requirements of both Types I and II and label the product as Type I/II Portland cement, Figure 21.8. Approximately 90% of all Portland cement used is Type I (or Type I/II) followed by Type III (approximately 5%).

The particle size of Portland cement affects its performance. The finer the particles, the greater the surface area available for water to coat cement particles. This increases the rate of hydration, leading to higher early strength of Portland cement paste. Type III Portland cement, therefore, has finer particles than the other types.

txi
TYPE I/II
PORTLAND CEMENT
PORTLAND CEMENT
VAPOR BARRIER PROTECTED

FIGURE 21.8 Type I/II Portland cement. A Portland cement bag (1 ft^3) generally weighs 94 lb.

TABLE 21.1 PORTLAND CEMENT TYPES AND THEIR USES

Portland cement type	Description and use
I	**General-purpose** Portland cement, used where there is no special requirement
II	**Moderate-sulfate-resistant and moderate-heat-of-hydration** Portland cement
III	**High-early-strength** Portland cement, used in precast elements and where high early strength is required, such as in cold weather
IV	**Low-heat-of-hydration** Portland cement, used in massive civil engineering structures
V	**Sulfate-resistant** Portland cement, used where high sulfate resistance is required

EXPAND YOUR KNOWLEDGE

Composition of Portland Cement

Complex calcium compounds are formed during the heating of raw materials in a rotary kiln. These compounds impart different properties to Portland cement, and their relative proportions determine the type of Portland cement. These compounds are

Tricalcium silicate (C_3S)—called *alite*—approximately 50%
Dicalcium silicate (C_2S)—called *belite*—approximately 25%
Tricalcium aluminate (C_3A)—called *celite*—5% to 12%
Tetracalcium-alumino-ferite (C_4AF)—called *iron*—up to 8%

EXPAND YOUR KNOWLEDGE (*Continued*)

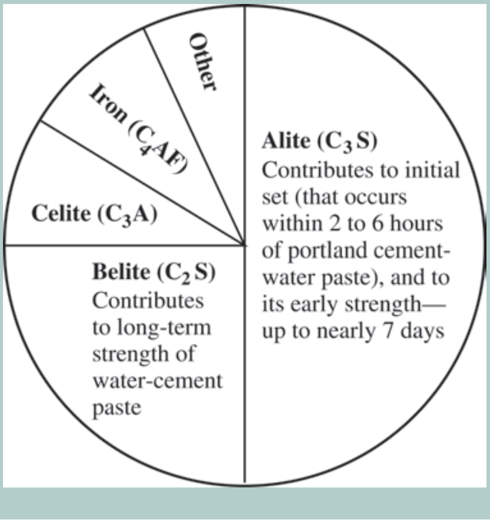
Alite hydrates rapidly. It is responsible for initial set and early strength (from one to seven days). Belite hydrates slowly and contributes to later strength gain (28+ days).

Celite liberates a great deal of heat in the initial few days and contributes somewhat to early strength. Too much celite can reduce the sulfate resistance of Portland cement.

Iron has little impact on Portland cement properties but is needed as a flux to reduce energy consumption during manufacturing. A flux reduces the temperature at which the raw materials begin to melt and coalesce. The characteristic gray color of Portland cement is due to the presence of iron and a small amount of manganese. White Portland cement is made by reducing the iron and manganese contents.

Gypsum (calcium sulfate) is added to increase the setting time of Portland cement. *Setting* is stiffening (early hardening) of the mix, that is, when the mix becomes semisolid. The mix should set neither too rapidly nor too slowly. A rapid set does not give enough time for placing and finishing the mix. A slow set delays finishing operations such as troweling and floating. Set control is, therefore, important. The amount of gypsum is carefully controlled.

Portland cement has a small quantity of alkalis—sodium and potassium oxides—which can react adversely with some forms of aggregates used in concrete.



21.4 AIR-ENTRAINED AND WHITE PORTLAND CEMENTS

The Portland cement types previously described are the basic types. These types are also available with an integrally combined air-entraining agent. Air entrainment in concrete, mortar, or plaster increases the durability of these materials against freezing and thawing.

The process of placing concrete in forms requires a much greater amount of water in a mix (called the *water of convenience*) than that required for the chemical reaction between Portland cement and water (see Section 21.9). An inadequate amount of water in concrete does not allow concrete to be fluid enough to flow into the form and fill it completely. This results in honeycombed concrete. The excess water in a concrete mix evaporates as it stiffens, leaving voids. These voids are in addition to the voids between concrete ingredients—Portland cement and aggregate—and those caused by lack of (or poor) consolidation. These voids contain *entrapped air*.

Because of the entrapped air, concrete is porous and tends to absorb rainwater. During freezing weather, the absorbed water turns into ice and expands. If a concrete is critically saturated and undergoes cycles of freezing and thawing, it will spall unless air voids are present to dissipate the pressure caused by the increased volume. To reduce freeze-thaw damage, tiny particles of air are introduced in a concrete mix, referred to as *air entrainment*. As the absorbed water in concrete expands on freezing, the entrained air relieves the pressure. Air-entrained concrete is commonly specified in exposed concrete elements subjected to freeze-thaw cycles.

Air entrainment can be achieved in two ways. The preferred way is to add an air-entraining chemical to the mix, referred to as an *air-entraining admixture*. The alternative is to use an air-entrained Portland cement. Air-entrained Portland cement has an air-entraining chemical as its integral part. All five basic types of Portland cement are available as air-entrained Portland cement. They are identified as Types IA, IIA, IIIA, IVA, and VA. With an air-entraining admixture, normal Portland cement (Type I, II, III, IV, or V) is used.

NOTE

Entrapped Air versus Entrained Air in Concrete

Entrapped air in concrete does not provide freeze-thaw resistance because it is not uniformly distributed in concrete and the air particle size is too large to be effective (generally 1 mm or larger). Additionally, entrapped air voids are irregular in shape and are generally interconnected.

Entrained air voids, on the other hand, are much smaller (10 to 100 μm in size), almost spherical in shape, and uniformly distributed in concrete, but not interconnected.

A typical (non-air-entrained) concrete has an air content of approximately 1.5%. An air-entrained concrete requires about 6% air in order to provide high freeze-thaw resistance.

WHITE PORTLAND CEMENT

The more commonly used Portland cement is gray in color. For aesthetic reasons, white Portland cement is preferred, particularly for terrazzo flooring, stucco, and architectural concrete. Colored aggregates in a terrazzo floor show up much better against a background of white Portland cement. Additionally, when pigments are added to white Portland cement, the resulting color is better than that obtained with the use of gray Portland cement.

White Portland cement is made by reducing the iron and manganese contents. This complicates the manufacturing process and increases the energy cost. Consequently, white Portland cement is approximately twice the cost of normal (gray) Portland cement. However, because Portland cement is only one part of a concrete or stucco mix, the final product may only be 50% more expensive.

FIGURE 21.9 A white Portland cement bag.

Like the gray cement, white Portland cement is available in bags, Figure 21.9, or in bulk. It is generally produced as Type I or Type III. These types have the same properties as the gray Type I and Type III Portland cement, respectively.

21.5 BASIC INGREDIENTS OF CONCRETE

The art and science of making concrete virtually disappeared after the fall of the Roman Empire until the discovery of Portland cement approximately 1,400 years later. As stated previously, modern concrete is similar to Roman concrete, except that in modern concrete, Portland cement is used as the glue to bind the stone aggregate together instead of a mixture of lime and volcanic ash.

The basic ingredients of modern concrete are Portland cement paste (i.e., Portland cement and water) and aggregate. Together, these materials provide a hard, rocklike substance, that is durable, fire resistant, and relatively inexpensive. It is used universally because virtually every region of the earth has the raw materials necessary to produce it. Additionally, the technology associated with its production and use is fairly simple.

Unlike other structural materials, concrete can be formed to any desired shape. In fact, an entire structure, regardless of its shape or size, can be formed monolithically—as if it were one object (*mono* means "one," and *lithos* means "piece of stone"). Some pioneers of the modern movement in architecture (e.g., Le Corbusier and Frank Lloyd Wright) and several structural engineers (e.g., Robert Maillart and Pier Nervi, and, more recently, Santiago Calatrava) have exploited the sculptural property of concrete, Figures 21.10 and 21.11.

NOTE

What Is Concrete?

Concrete consists of:

- Aggregate (coarse and fine aggregate) as matrix or filler
- Portland cement–water paste as an adhesive

Any other material used in concrete is called a *concrete admixture* (see Sections 21.10 and 21.11).

SIZE OF THE AGGREGATE

Aggregate in concrete occupies 65% to 80% of the volume of concrete, the remainder being Portland cement. The aggregate must consist of different-sized particles, referred to as *size gradation*. Proper gradation ensures that smaller particles fit within the voids created by larger particles, so that the entire mass of concrete is relatively dense, Figure 21.12(a).

A well-graded aggregate (implying that it consists of particles of various sizes) not only gives a stronger concrete, but also reduces the amount of Portland cement necessary to wrap the particles and fill the spaces between them. An aggregate that consists of particles of only one or two sizes has a higher percentage of voids and, therefore, requires a much larger amount of Portland cement, Figure 21.12(b). Because Portland cement is far more expensive than aggregates, this gives an uneconomical concrete.

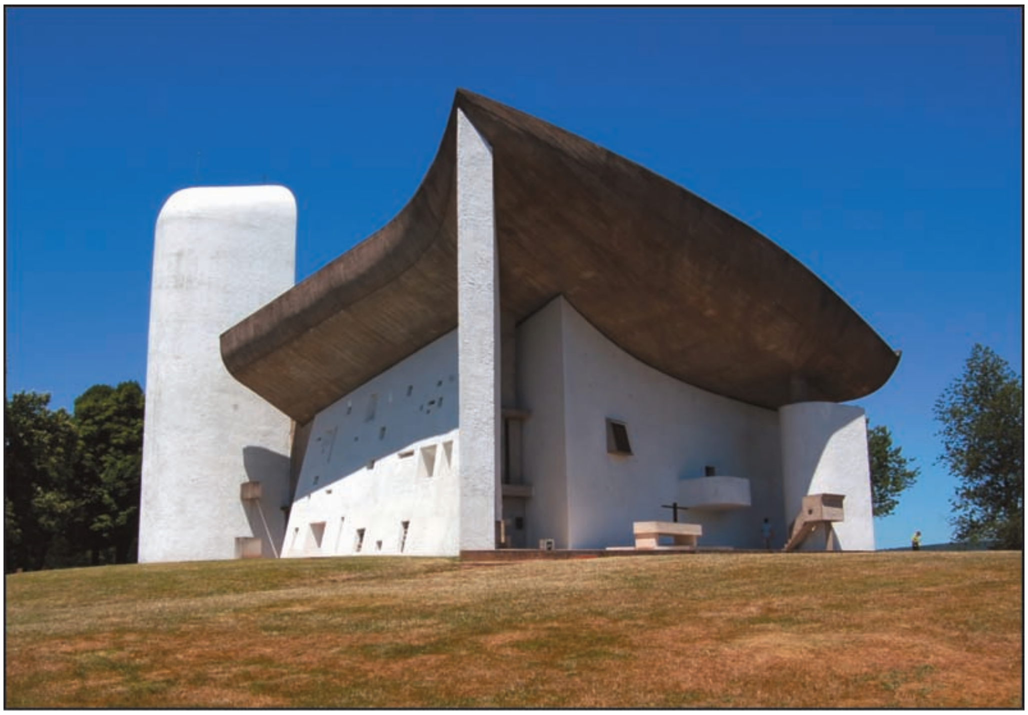


FIGURE 21.10 Chapel at Ronchamp, France, by architect Le Corbusier. Le Corbusier was among the pioneers in exploiting the sculptural properties of concrete in building structures. (Photo by jps Shutterstock)

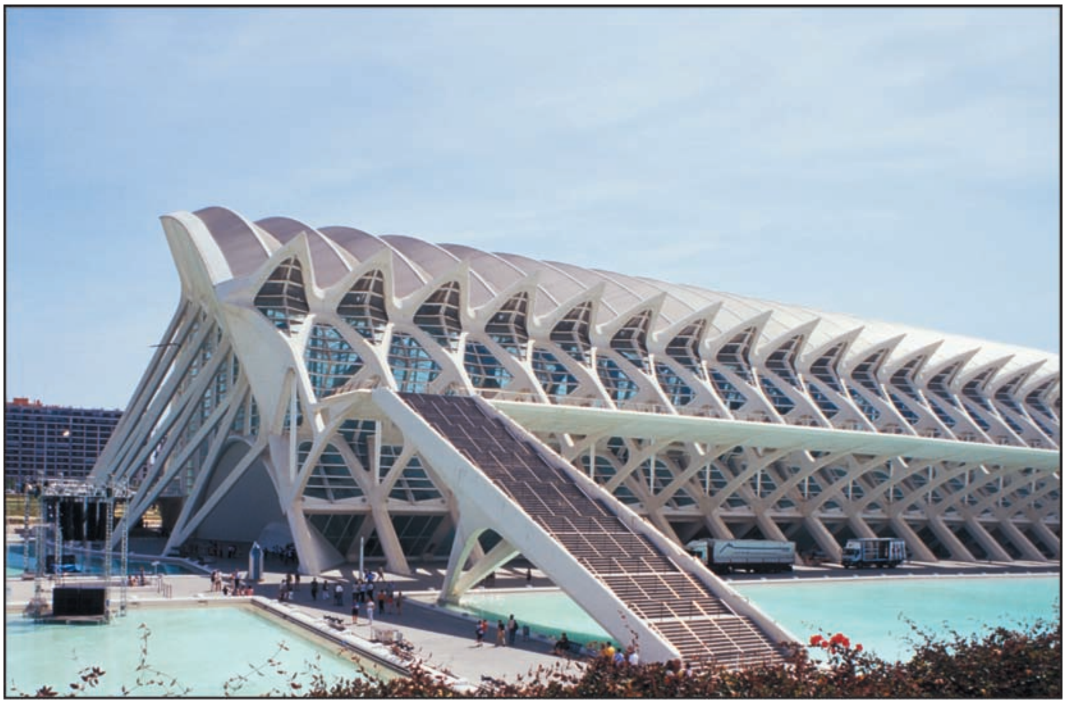


FIGURE 21.11 Concrete structural frame work in the City of Arts and Sciences, Valencia, Spain, by architect-engineer Santiago Calatrava, illustrating the sculptural properties of concrete.

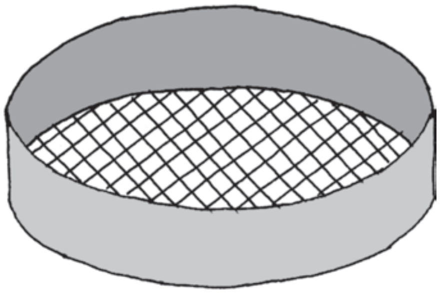
NOTE

Gravel

Gravel consists of naturally occurring rock particles of 0.2 in. to 3 in. in size (see Figure 11.1). Because gravel is formed by erosion and weathering of rocks, it is round in shape, in contrast to crushed stone. The term *pea gravel* refers to gravel that is approximately $\frac{1}{4}$ in. to $\frac{3}{8}$ in. in size.

In general, therefore, the aggregate in a concrete mix consists of several sizes. However, the concrete industry divides the aggregate into two size groups:

- Fine aggregate
- Coarse aggregate



A typical sieve used for grading of aggregates in concrete laboratories. The sieves used in a concrete laboratory are the same as those used in a geotechnical laboratory. A No. 4 sieve has wires spaced at $\frac{1}{4}$ in. (0.25 in.) on center, a No. 10 sieve has wires at $\frac{1}{10}$ in. (0.1 in.) on center, and so on. The clear opening between wires in a No. 4 sieve = 4.75 mm and that of a No. 10 sieve = 2.00 mm (see Figures 11.1 and 11.4).

Fine aggregate is generally sand, but more precisely it is that material of which 95% passes through a No. 4 sieve. A No. 4 sieve consists of a wire mesh with wires spaced at $\frac{1}{4}$ in. on center. Because the wires have a certain standard thickness, the largest particle size of fine aggregate that can pass through a No. 4 sieve is slightly smaller than $\frac{1}{4}$ in.

Fine aggregate needs to be graded from a No. 4 sieve down to a No. 100 sieve. Recommended grading is shown in Table 21.2.

Coarse aggregate is that aggregate of which 95% is retained on a No. 4 sieve. It consists of either crushed stone or gravel. Gravel has several advantages over crushed stone, but crushed stone is commonly used because it is more economical.

Although the minimum size of coarse aggregate is limited by the No. 4 sieve, its maximum size is a function of the smallest dimension of the building element and the spaces between steel reinforcement. For example, the American Concrete Institute (ACI) Code requires that for a concrete wall, the maximum coarse aggregate size should be smaller than one-fifth of the thickness of the wall. Obviously, if the

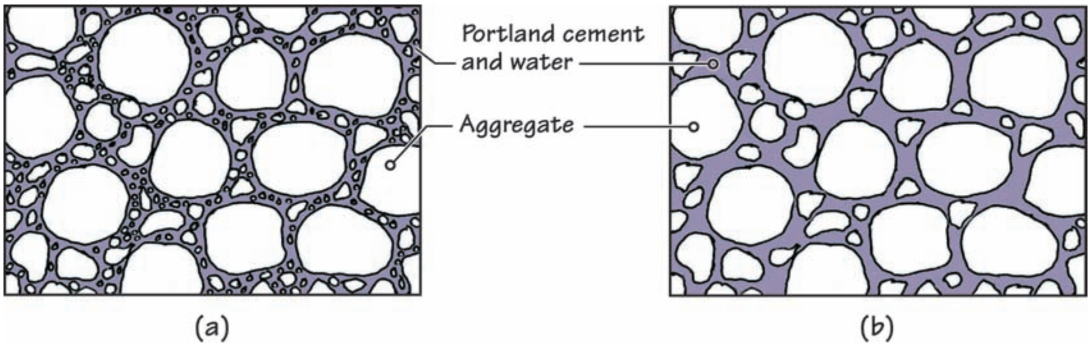


FIGURE 21.12 **(a)** Well-graded aggregate. **(b)** Poorly graded aggregate. The colored areas in these illustrations represent Portland cement and water paste. Observe that poorly graded aggregate requires a greater amount of Portland cement.

TABLE 21.2 RECOMMENDED GRADING OF FINE AGGREGATE FOR CONCRETE SLABS

Sieve size	Percent of aggregate passing through a sieve
$\frac{3}{8}$ in.	100
No. 4	95–100
No. 8	80–90
No. 16	50–75
No. 30	30–50
No. 50	10–20
No. 100	2–5

size of coarse aggregate is too large for the space in which it is placed, it will be difficult to consolidate, giving nonhomogeneous and inconsistent concrete.

Similarly, if the steel reinforcement is closely spaced, the maximum coarse aggregate size must be small. The objective is that the concrete should flow easily around the reinforcement. In most concrete used in buildings, the maximum coarse aggregate is $\frac{3}{4}$ in. Concrete used in thick walls and heavy foundations may have aggregate up to $1\frac{1}{2}$ in. in size; it may be up to 6 in. in dam walls.

The size of coarse aggregate has a bearing on the concrete's cost. Larger particles have a smaller surface area for a given volume. Therefore, concrete made with large particles requires less Portland cement, giving a more economical concrete, Figure 21.13.

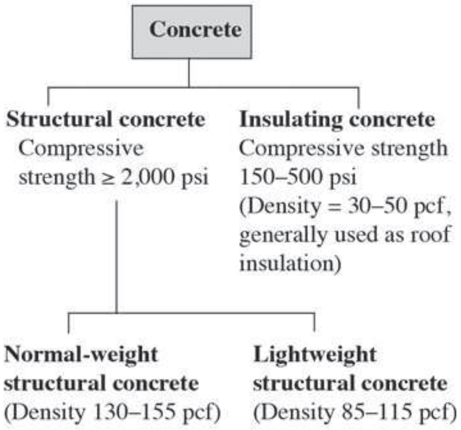
NORMAL-WEIGHT AND LIGHTWEIGHT COARSE AGGREGATES

Concrete may either be structural or nonstructural. Nonstructural concrete is generally insulating concrete, which is used as roof insulation (see Chapters 5 and 33). Structural concrete is used in a structural frame—beams, slabs, columns, and walls.

The most commonly used structural concrete has a compressive strength of 4,000 psi. However, any concrete with a compressive strength of 2,000 psi or above is considered to be structural concrete. Structural concrete may either be normal-weight or lightweight concrete.

The American Concrete Institute Code defines lightweight structural concrete as one that, in its hardened state, weighs 85 to 115 lb/ft^3. Normal-weight concrete weighs 130 to 155 lb/ft^3. The difference between normal-weight and lightweight structural concretes is only in the type of coarse aggregates used. The fine aggregate in both is the same.

Normal-weight concrete is obtained using normal-weight aggregate. These aggregates include crushed limestone, granite, quartz, and so on. Lightweight structural concrete is obtained using lightweight aggregate.


Concrete
Structural concrete
Compressive strength ≥ 2,000 psi
Insulating concrete
Compressive strength 150–500 psi (Density = 30–50 pcf, generally used as roof insulation)
Normal-weight structural concrete (Density 130–155 pcf)
Lightweight structural concrete (Density 85–115 pcf)

NOTE

Cost of Concrete and Coarse Aggregate Size

In a concrete mix, Portland cement paste coats the surface of aggregates. If the surface area of aggregates is small, the amount of cement paste needed is small. Large aggregates have a small surface area for a given volume. Therefore, everything else being the same, a mix consisting of larger aggregates is more economical.

That the surface area of smaller particles contained in a given volume is greater than that of larger particles can be explained by considering 2-in. and 1-in. cubes. The surface area of a 2-in. cube is 24 in.^{2}, and its volume is 8 in.^{3}.

Now consider 1-in. cubes. To obtain a volume of 8 in.^{3} using 1-in. cubes, eight cubes are needed. The surface area of these eight cubes is $8 \times 6 = 48$ in.^{2}—double that of a 2-in. cube. Thus, the use of half-size particles has doubled the surface area, although the space occupied by the particles has not changed.

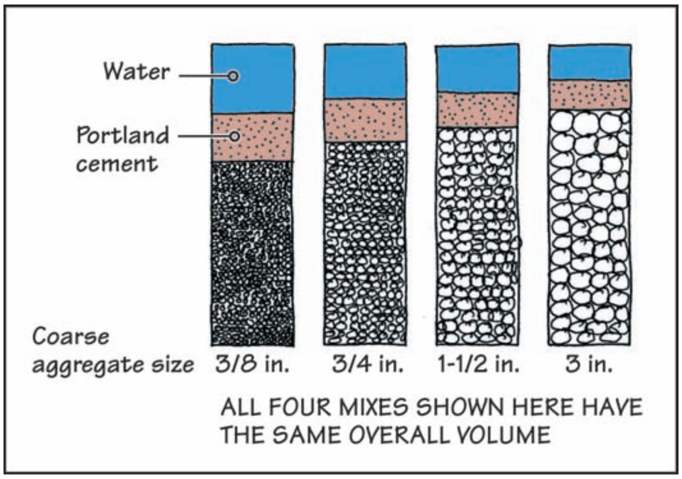

Water
Portland cement
Coarse aggregate size
3/8 in.
3/4 in.
1-1/2 in.
3 in.
ALL FOUR MIXES SHOWN HERE HAVE THE SAME OVERALL VOLUME

FIGURE 21.13 Effect of aggregate size on the amount of cement-water paste. The four mixes shown here have the same overall volume. Note that as the size of aggregate increases, the amount of cement-water paste needed for a given volume of concrete decreases. Because Portland cement is the major cost-contributing ingredient in a mix, concrete with larger aggregate is generally more economical.

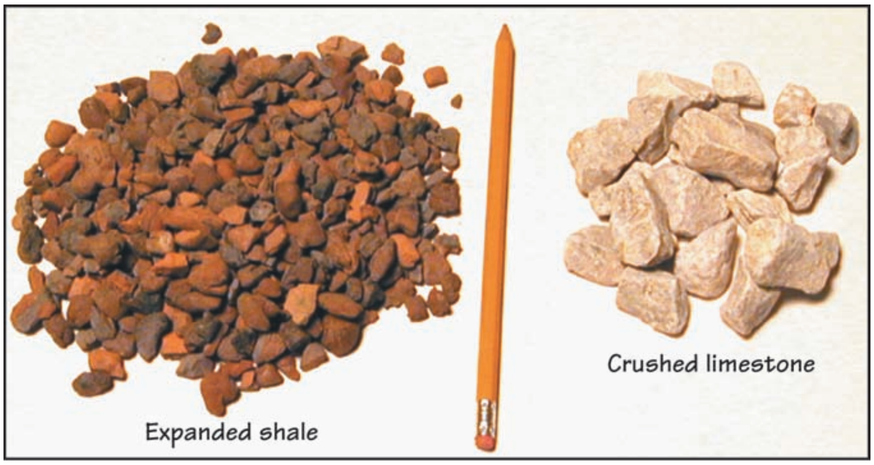


FIGURE 21.14 Two commonly used aggregates in concrete—crushed limestone as normal-weight aggregate and expanded shale as lightweight aggregate. The quantities shown here are such that both aggregate piles have the same approximate weight. Expanded shale, being fired clay, is generally brown in color, similar to that of a fired clay brick.

One commonly used lightweight aggregate is expanded shale, obtained by heating crushed shale to a high temperature. This converts any water present in a shale particle into steam, which—in trying to exit—expands the particle, reducing its density. Because it is a baked material and because shale is a compressed form of clay, the color of expanded shale is similar to that of brick. Figure 21.14 portrays the difference between normal-weight limestone aggregate and lightweight expanded shale aggregate.

Lightweight structural concrete costs more than normal-weight concrete because of the higher cost of producing the aggregate. However, it can yield savings in the overall cost of the structure because it reduces dead loads. This is particularly attractive in a high-rise structure, where any reduction in the dead load of floor slabs reduces the size of supporting beams. This, in turn, reduces the size of columns, which leads to lighter foundations.

Lightweight structural concrete has, however, limitations as to strength. High-strength concrete is difficult to obtain using lightweight aggregates. However, the commonly used concrete strength of 4,000 psi is easily obtained using lightweight aggregates. Therefore, in a high-rise structure, lightweight concrete is used in floor beams and slabs, and normal-weight concrete is used in columns. The reason is that, whereas the columns have to support the load of all the upper floors, the floor beams and slab are required to support only the load of one floor.

QUALITY OF WATER

Water is an important component of concrete. Portland cement derives its cementing property from its reaction with water. Water used in concrete must be clean. A rule of thumb in the concrete industry is that if the water is fit for drinking, it is fit for use in concrete. Because seawater contains salts, its use leads to corrosion of reinforcing steel. It also modifies the Portland cement–water reaction and is, therefore, not appropriate for use.

NOTE

Carbonate versus Silicious Aggregates

Concrete aggregates are generally obtained from limestone, granite, quartz, sandstone, and so on. Limestone (calcium carbonate) aggregate yields concrete that is slightly more fire resistant than the concrete obtained from aggregates produced from granite, quartz, sandstone, and so on.

In general, carbonate-containing aggregates give a concrete that is more fire resistant than that obtained from silicious aggregates (see Table 23.1).

NOTE

Wash Water

Concrete mixers are washed after delivery and before being recharged with the next batch. Ready-mix plants are increasingly using the wash water in the mix—a more sustainable alternative.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

10. The main ingredient used in the manufacture of Portland cement is
- **a.** marble.
- **b.** granite.
- **c.** limestone.
- **d.** sand.
- **e.** iron ore.

11. ASTM specifications classify Portland cement into five basic types, referred to as
- **a.** Types A, B, C, D, and E.
- **b.** Types I, II, III, IV, and V.
- **c.** Types PC1, PC2, PC3, PC4, and PC5.
- **d.** Types X, Y, Z, P, and Q.
- **e.** none of the above.

12. The most commonly specified type of Portland cement is
- **a.** Type C.
- **b.** Type III.
- **c.** Type PC1.
- **d.** Type I/II.
- **e.** Type II/III.

13. Which type of Portland cement is commonly used in making precast concrete members?
- **a.** Type C
- **b.** Type III
- **c.** Type PC1
- **d.** Type I/II
- **e.** Type II/III

14. White Portland cement is generally weaker than normal (gray-colored) Portland cement.
- **a.** True
- **b.** False

(*Continued*)

PRACTICE QUIZ *(Continued)*

15. The aggregate for concrete is generally subdivided into coarse aggregate and fine aggregate. The distinction between the two types of aggregate is based on the

a. aggregate's strength.
b. aggregate's surface texture.
c. aggregate's density.
d. aggregate's particle size.
e. aggregate's parent rock.

16. In a No. 4 sieve, the dimensions of voids are approximately

a. 4 in. × 4 in.
b. $\frac{1}{4}$ in. × $\frac{1}{4}$ in.
c. 2 in. × 2 in., giving an area of approximately 4.0 in.^{2}.
d. 1 in. × 4 in.
e. none of the above.

17. A well-graded coarse aggregate is one in which the size of all aggregate particles is approximately the same.

a. True
b. False

18. Everything else being the same, a concrete with a larger coarse aggregate requires less Portland cement and water paste to give the same concrete strength.

a. True
b. False

19. Lightweight structural concrete is heavier than insulating concrete.

a. True
b. False

21.6 IMPORTANT PROPERTIES OF CONCRETE

Properties of concrete that are of interest to architects, engineers, and builders may be divided into the following two categories:

- Fresh (plastic-state) concrete properties
- Hardened concrete properties

FRESH CONCRETE PROPERTIES—WORKABILITY (SLUMP) OF CONCRETE

A good concrete mix should be able to retain its homogeneity (nonsegregation of particles) during all operations involved in transporting the concrete from the mixer to the form and placing, compacting, and finishing the concrete. Additionally, it should be possible to perform these operations with relative ease and in a reasonable amount of time. In other words, a good concrete should be easy to pump (when required), place, and compact, and it should set within a reasonable amount of time so that finishing can be done without delay.

Whether a concrete meets these requirements or not can often be judged visually by an experienced concrete technician. However, a measure commonly used to describe them collectively is called *workability*. Workability of concrete is the ease with which a concrete can be placed and compacted in the form with minimum loss of consistency and homogeneity. Concrete that is not workable is referred to as a *harsh* concrete. To obtain a workable concrete:

- The aggregates should be well graded.
- Everything else being the same, large aggregates reduce workability. Adequate fine material is important in providing a workable concrete. That is why the addition of fly ash or silica fume, for example, in a mix improves its workability. Because the particle size of Portland cement is small, increasing the amount of Portland cement also increases workability. However, excessive Portland cement in a mix makes it too gluey and tacky, reducing workability.
- The aggregates should not be too angular in shape. Gravel, because of its naturally round particles, gives greater workability than crushed stone. However, crushed stone, if properly graded, yields good workability. Similarly, sand obtained from river beds or mined from sand pits gives greater workability than that obtained by crushing and pulverizing stone.
- An adequate amount of water is necessary for workability.

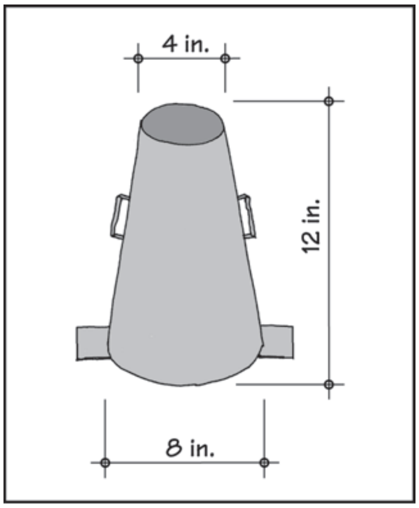
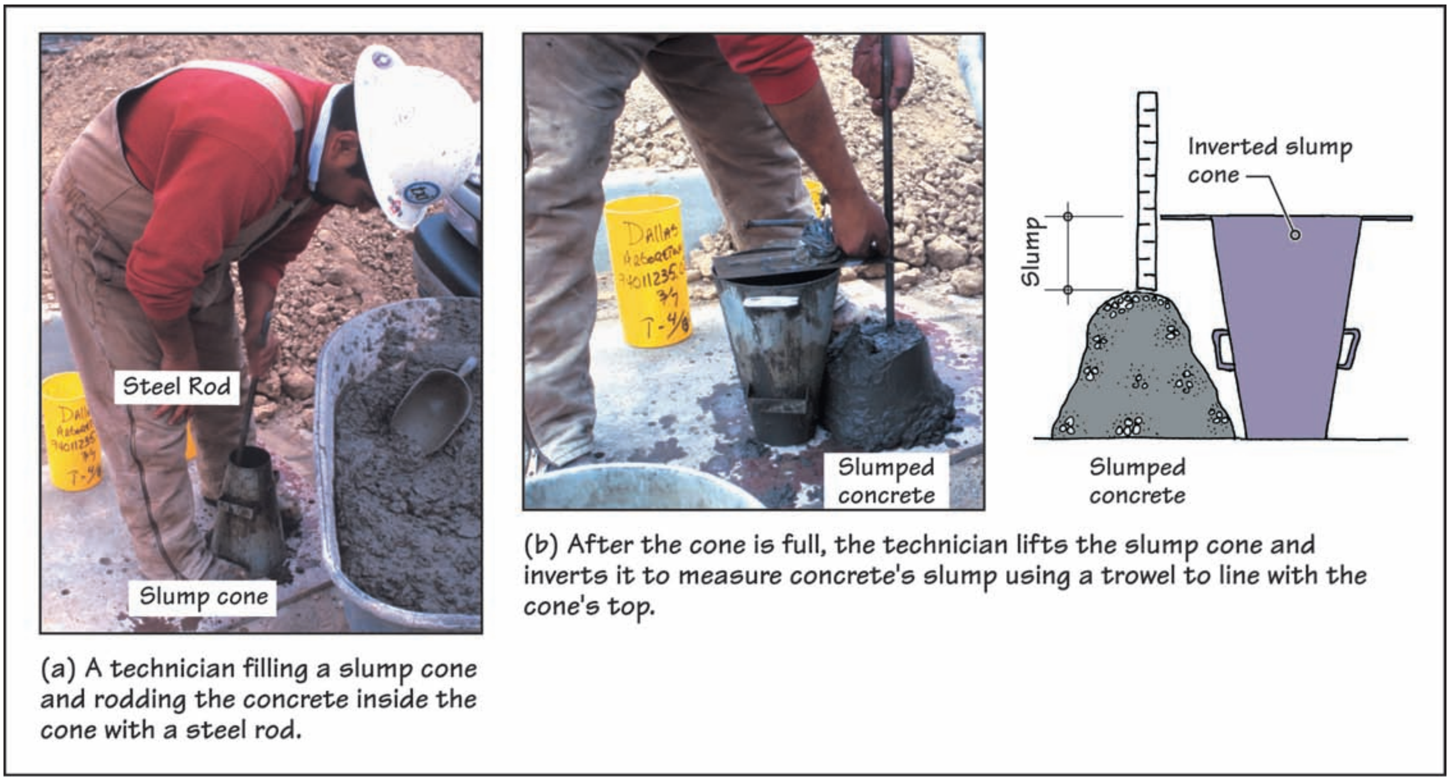


FIGURE 21.15 A slump cone is open at the top and bottom.

A commonly used measure of workability is *slump*. Although slump does not evaluate all aspects of workability, it is its best available measure. The slump of concrete is measured using a truncated cone. The cone is open at the top and bottom and has handles and foot tabs. It measures 4 in. at the top and 8 in. at the bottom and is 12 in. high, Figure 21.15.

Slump measurements are performed by a qualified concrete technician at the construction site immediately after the concrete is received. To measure slump, the inside surface of the slump cone is dampened with water, and any old concrete sticking to its surface is removed.

The cone is placed on a rigid, flat, smooth, and nonabsorbent surface. It is held firmly in place by standing on foot tabs, Figure 21.16(a). Concrete is placed in the cone in three layers,



(a) A technician filling a slump cone and rodding the concrete inside the cone with a steel rod.

(b) After the cone is full, the technician lifts the slump cone and inverts it to measure concrete's slump using a trowel to line with the cone's top.

FIGURE 21.16 Measurement of the slump of concrete.

each 4 in. high (as per ASTM C143). Each layer is tamped 25 times through its depth by a $\frac{5}{8}$-in.-diameter smooth steel rod—a process also referred to as *rodding*.

After the last layer has been fully rodded, the excess concrete is struck off so that the concrete is flush with the top of the cone. The cone is then removed with a slow upward motion. As soon as the cone is removed, the concrete settles. The slump of concrete is a measure of settlement in inches—the difference between the 12-in. height of the cone and the top of the slumped concrete, Figure 21.16(b).

Workable concrete will slump uniformly, retaining its overall conical profile. A poorly graded concrete will slump nonuniformly.

Different slumps are required for different applications of concrete. A low value of slump gives a concrete that will not completely flow in the form and will require careful compaction.

In some situations, a high-slump concrete is desired, such as in the grout used in masonry walls. In most situations (unless a water-reducing admixture has been used; see Section 21.10), a high value of slump indicates the use of excess water. This, as we will see later, reduces concrete's strength. Generally, for concrete walls, columns, and beams, a slump of 4 in. to 5 in. is required. For slabs, a slump of 3 in. to 4 in. is generally adequate.

NOTE

Approximate Required Slump Values

Walls and columns	4–5 in.
Beams	4–5 in.
Slabs	3–4 in.

FRESH CONCRETE PROPERTIES—PARTICLE SEGREGATION AND BLEEDING

If concrete is not carefully placed in the forms or if it is compacted excessively, larger aggregates settle down and smaller ones rise to the top. The segregation of particles gives a non-homogeneous concrete, reducing its strength. It is important, therefore, that concrete be placed in position carefully and not thrown from a large distance.

Segregation of aggregates is generally accompanied by *bleeding*. Bleeding is the rising of water to the top. This is similar to the rise of water that occurs in a heap of wet sand on a beach when tapped a few times. Bleeding occurs naturally when the mix is compacted or floated. Therefore, a certain amount of bleeding is inherent during placing, compacting, and finishing. Excessive bleeding should be avoided.

HARDENED CONCRETE PROPERTIES—COMPRESSIVE STRENGTH OF CONCRETE

The two most important properties of hardened concrete are durability and compressive strength. The first step in determining concrete's strength is to cast test cylinders from the concrete received at the job site. The casting of cylinders and the slump test are generally performed at the same time.

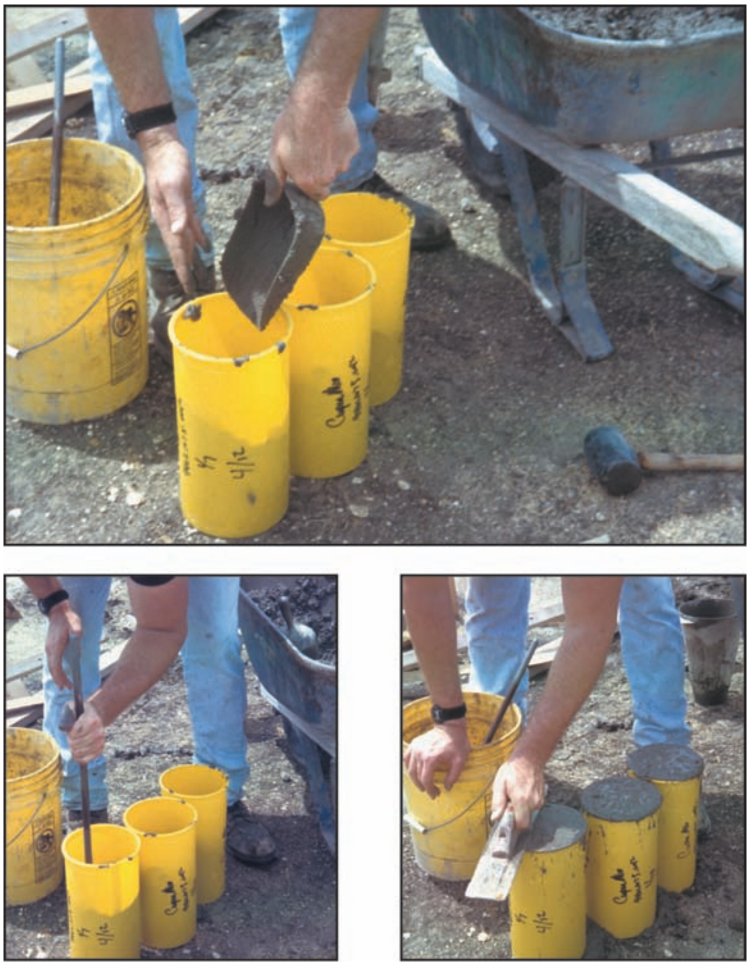
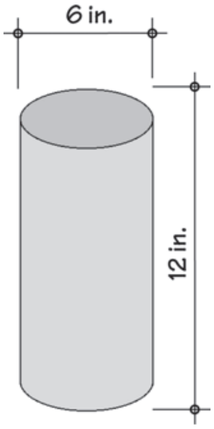


FIGURE 21.17 Casting of concrete test cylinders.



Dimensions of a concrete test cylinder

A concrete cylinder is 6 in. in diameter and 12 in. high. Building codes and standards specify the number of test cylinders that must be cast for a certain amount of concrete used. A concrete test cylinder is made by placing concrete in a mold in three layers, similar to the slump test. Each layer is rodded 25 times, and finally the excess concrete is struck off, leaving it flush with the top of the mold, Figure 21.17.

The molds for cylinders are generally of plastic, steel, or coated cardboard. Plastic and steel molds are slightly oiled before being filled with concrete. Cardboard molds have an integral waterproofing on the inside surface. The outside of a mold is identified with an indelible marker as to the job site and the date of casting. After the molds have been cast, their tops are covered with a plastic sheet to retain the water in the concrete. They are kept at the construction site for 24 h after casting, care being taken to ensure that they remain undisturbed for this period.

After 24 h, they are carefully transported to a concrete testing laboratory, where the molds are stripped off the cylinders. At the time of removal of the molds, the identifying information is transferred to the cylinders, which are then placed in a moist chamber. The air in a moist chamber is fully saturated at approximately 73°F (20°C). The cylinders remain in the moist chamber until they are tested to failure. Some research laboratories that do not have a moist chamber use a water tank in which the cylinders are kept immersed.

As described later, concrete develops its strength over a long period of time. The typical concrete strength used for design purposes is its 28-day strength. Cylinders are, therefore, generally tested 28 days after casting. To determine the strength of concrete, the cylinders are removed from the moist chamber (or water tank) and crushed to failure, Figure 21.18. The compressive strength of concrete is simply the failure load divided by the cross-sectional area of the cylinder (see Chapter 4).

Because the top and bottom surfaces of a concrete cylinder are rough, they are capped with a smooth-surfaced material before the cylinder is placed in the test machine. Smooth ends give a more reliable test result. Rough ends lead to local crushing of protruding concrete particles, falsifying the result. Rough ends also misalign the cylinder; the cylinder must be in a vertical position in the machine. The capping material commonly used with cylinders is a 6-in.-diameter neoprene pad set in a steel containment ring. The containment ring prevents the neoprene pad from expanding laterally.

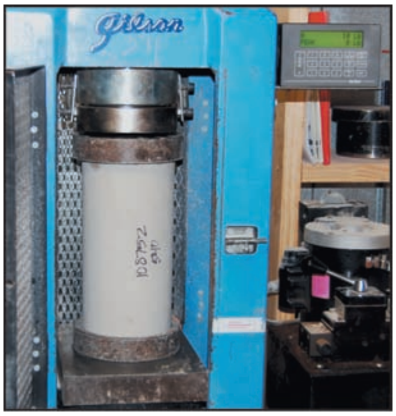


FIGURE 21.18 A concrete test cylinder in position in the testing machine, ready to be compressed to failure (see also Figure 4.6).

Concrete is the only building material whose quality is verified after it has been used in the building. Cylinder and slump tests verify that the concrete supplied by the concrete manufacturer has the strength and slump specified for the project.

21.7 MAKING CONCRETE

Concrete is made by mixing coarse and fine aggregates, Portland cement, and water. A small amount of concrete for a do-it-yourself job may be made by mixing various ingredients with a shovel, adding water, and mixing the ingredients further until all materials have blended. Alternatively, bags of dry concrete mix (consisting of premixed aggregates and Portland cement) may be obtained from a building material store. A dry concrete mix needs only the addition of water.

If a slightly larger quantity of concrete is required, an on-site mobile concrete mixer can be used, Figure 21.19. However, where even a small degree of control on the quality of concrete is required, the concrete should be obtained from a ready-mix plant. A ready-mix plant is a concrete-manufacturing facility. Approximately 95% of all concrete used in contemporary building construction is obtained from such a facility. Most cities in the United States have at least one ready-mix plant within the city or close by.

An important part of concrete manufacturing is *mix design*. Mix design involves determining the correct amounts of various ingredients to give a concrete that has the required durability, strength, workability, and any other property specified by the architect or engineer. Mix design is fairly complex and is covered in detail in texts devoted entirely to the subject. One reason for its complexity is the enormous variability in the quality of aggregates, even when they are obtained from the same source. A typical ready-mix plant has technical personnel with expertise on mix design.

Figure 21.20 shows an overview of a typical ready-mix plant. The most prominent and visible part of the plant is a set of cylindrical silos. The silos contain coarse aggregate, fine aggregate, and Portland cement. The aggregates are initially stockpiled in an open yard within the plant compound, Figure 21.21. From the stockpiles, the aggregates are conveyed into the silos as needed. The space directly under the silos is designed to hold a concrete mixer truck. Correct amounts of various materials are fed by gravity from the silos into the mixer, Figure 21.22.

Weighing the materials and charging the truck mixer are fully automated and are controlled from a central location that overlooks the charging operation, Figure 21.23. The first material fed into the mixer is usually water, followed by aggregates and Portland cement. A small amount of water may be added at the construction site if needed. During travel, the mixer drum is set to rotate, so that when the concrete arrives at the site, it is almost ready for discharge (with some site remixing, as needed). A typical concrete mixer truck holds 10 yd^3 of fresh concrete.

NOTE

Field Curing of Concrete Cylinders

To obtain the compressive strength of concrete that is representative of the field conditions, cylinders may be field cured.

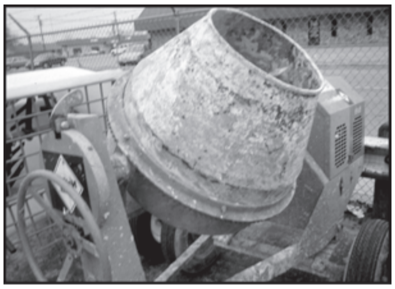


FIGURE 21.19 A transportable mixer for on-site mixing of small quantities of concrete.

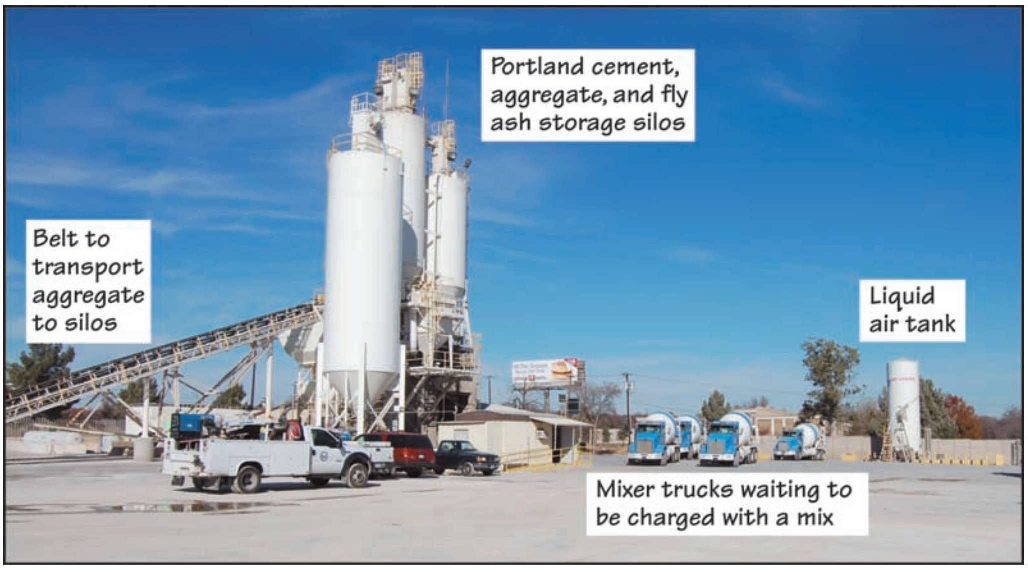

Portland cement, aggregate, and fly ash storage silos
Belt to transport aggregate to silos
Liquid air tank
Mixer trucks waiting to be charged with a mix

FIGURE 21.20 An overview of a ready-mix concrete plant. Liquid air may be needed in the concrete mix in warm weather to control its temperature. Ice may be used as an alternative, depending on availability and cost.

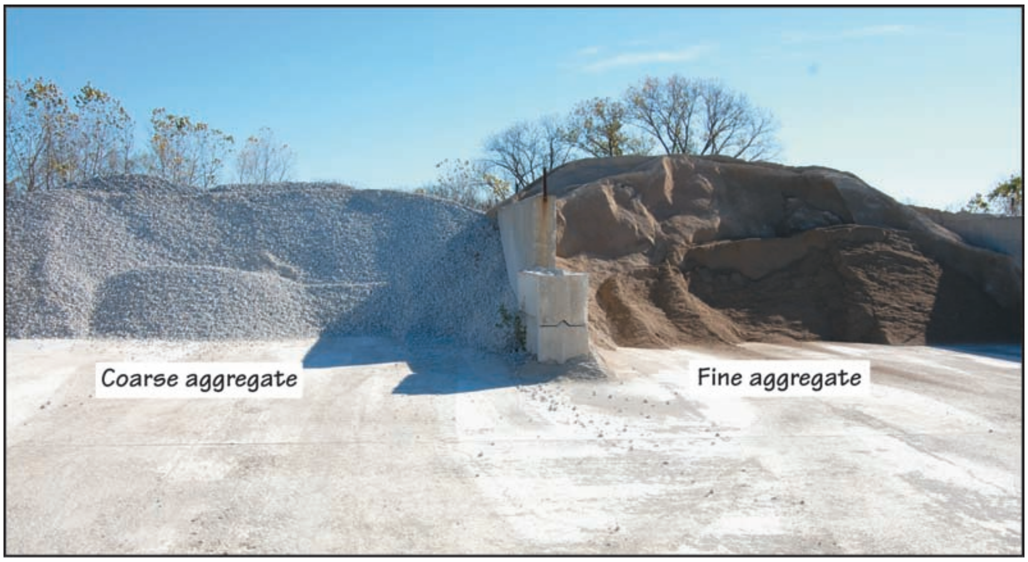


FIGURE 21.21 Stockpiles of coarse and fine aggregates in a concrete ready-mix plant. Observe the separation between different aggregates to ensure correct proportioning of the mix.

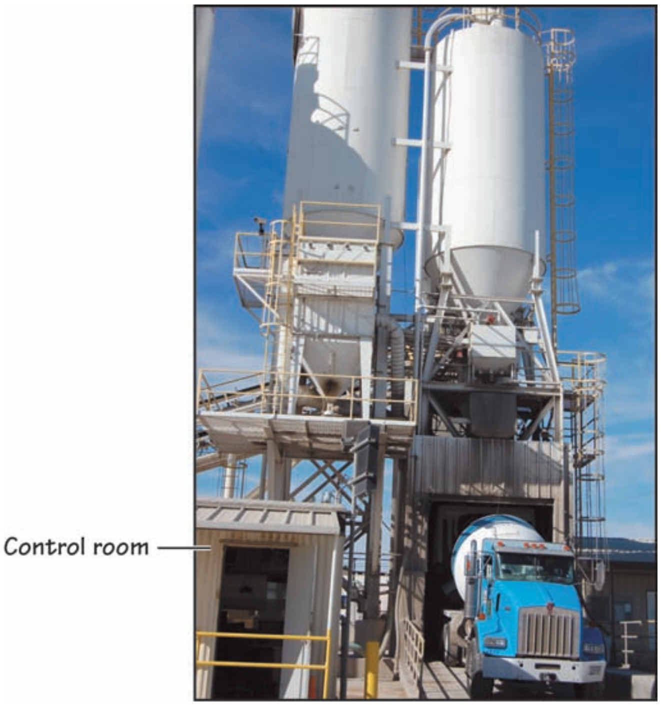


FIGURE 21.22 A truck mixer being charged with the mix. The control room is located adjacent to the charging station to allow the technician to observe and control the process. The control room has glazed openings toward the charging station; see Figure 21.23.

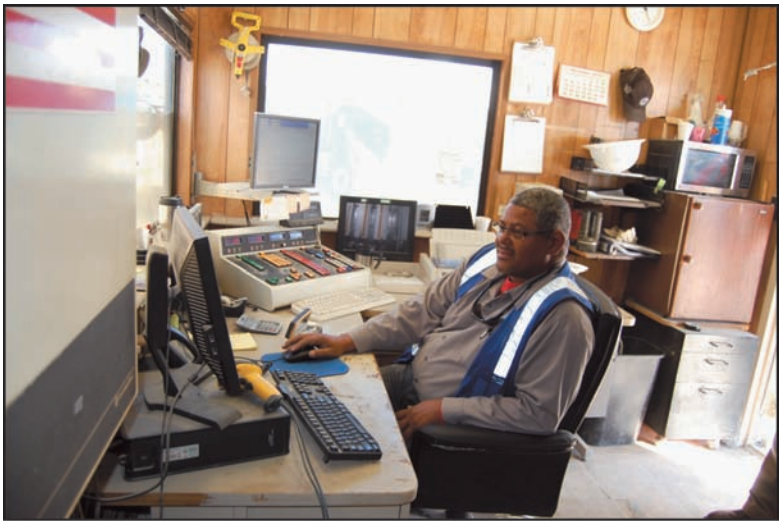


FIGURE 21.23 A typical control room in a ready-mix plant.

21.8 PLACING AND FINISHING CONCRETE

Because concrete begins to set within a few hours after the addition of water to the dry mix, it is a perishable material. Therefore, it must be placed in the desired position soon after being received at the construction site. Placing concrete requires transporting the concrete from the mixer truck to its final destination, that is, into the form of the building component. If the mixer truck can be parked fairly close to where the concrete is to be placed, the concrete can be delivered using a chute. A chute is simply an open steel channel that extends from the discharge end of the mixer to the concrete's destination, Figure 21.24. Almost every mixer has a few lengths of chute attached to it. A chute transports concrete by gravity and can only be used if the concrete's final destination is below the discharge end of the mixer.

Another method for placing concrete is to use buckets, Figure 21.25. Buckets are typically hoisted by cranes, but helicopters have been used in remote or demanding situations. The bucket method of transporting concrete is generally used for small quantities of concrete, where pumping is uneconomical.

Transporting concrete using a pump is common. It is particularly attractive where the construction site is spread over a large area and transporting concrete by chutes is not possible. Pumping is also used for high-rise structures in place of buckets. Pumping concrete is usually achieved by first transferring the concrete from the mixer to a pump truck. From the pump truck, the concrete is piped to the destination, Figure 21.26. The pump truck consists of a hopper into which the concrete is deposited. The hopper consists of a screen to ensure that undesirable materials that may clog the pipe or the pump are arrested by the screen, Figure 21.27.

CONCRETE CONSOLIDATION

Once the concrete has been placed in the form, it must be consolidated. *Consolidation* is the process of compacting concrete to ensure that it has no voids and air pockets. On a small job, consolidation can be done manually with the help of a steel rod, whereby the worker simply rods into the concrete—up and down and with some sideways motion. It is, however, more common to employ a high-frequency power-driven vibrator. This is typically an internal (or immersion) vibrator inserted into the concrete. An external vibrator is one that vibrates the form and is more commonly used in precast concrete plants.

An internal vibrator consists of a rod (1 to 3-in. diameter) connected to a flexible shaft, Figure 21.28. The vibrator is inserted into freshly placed concrete. As the concrete in a particular location is compacted, the vibrator is moved to the next location. Because the vibrator has a finite area of influence, the new insertion point must be fairly close to the previous insertion point. Excessive vibration must be avoided because it leads to particle separation and bleeding of concrete. For the same reason, concrete must be carefully placed in the forms, not dropped from an excessive height.

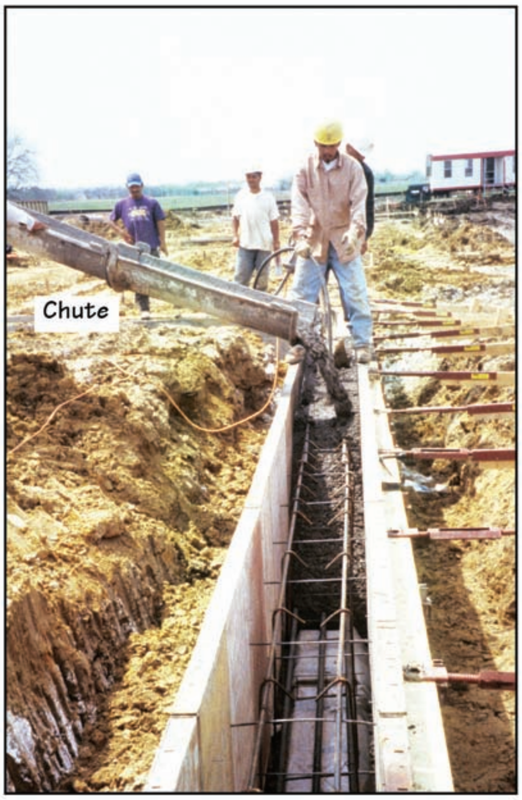


FIGURE 21.24 Concrete being brought into the formwork of a grade beam through an open chute from the mixer.

FINISHING THE CONCRETE SURFACE

After the concrete has been compacted, its exposed surfaces are finished while the concrete is still plastic. The exposed surfaces are those that are not covered by the formwork. The finishes include:

- Strike off (screeding)
- Floating (darbying)
- Troweling

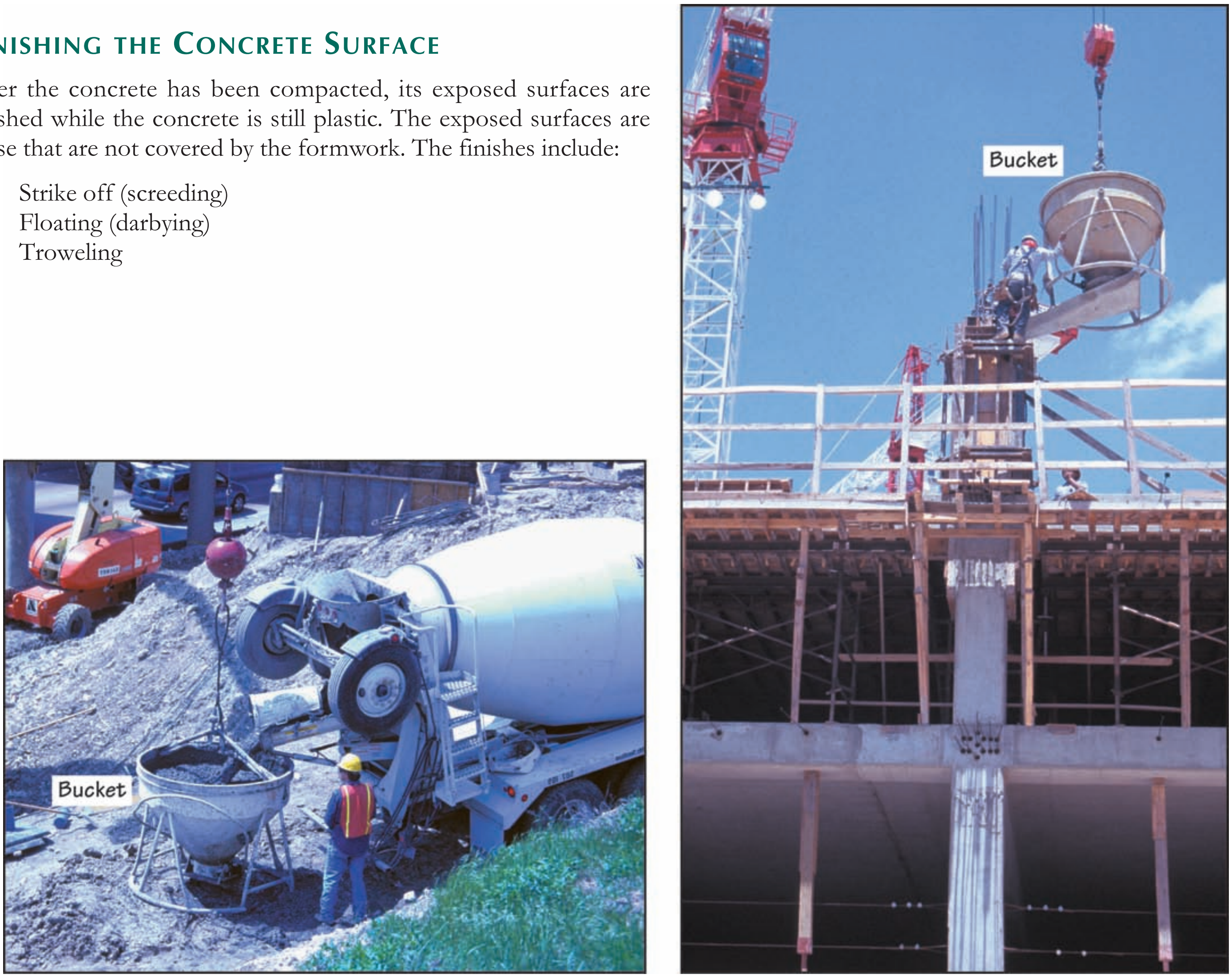


FIGURE 21.25 Concrete being filled in the bucket, which is hoisted into position using a crane. The bucket method of transporting concrete is generally used for small quantities of concrete, where pumping of concrete is uneconomical. Note that a large quantity of concrete is required to fill a pump line, which is wasteful if the quantity of concrete to be placed is small.

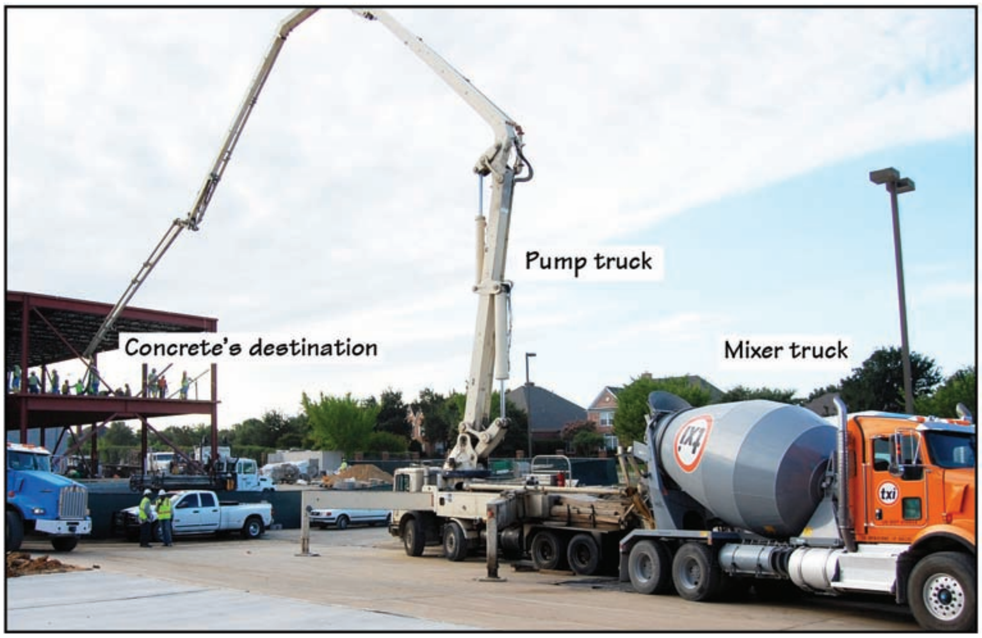
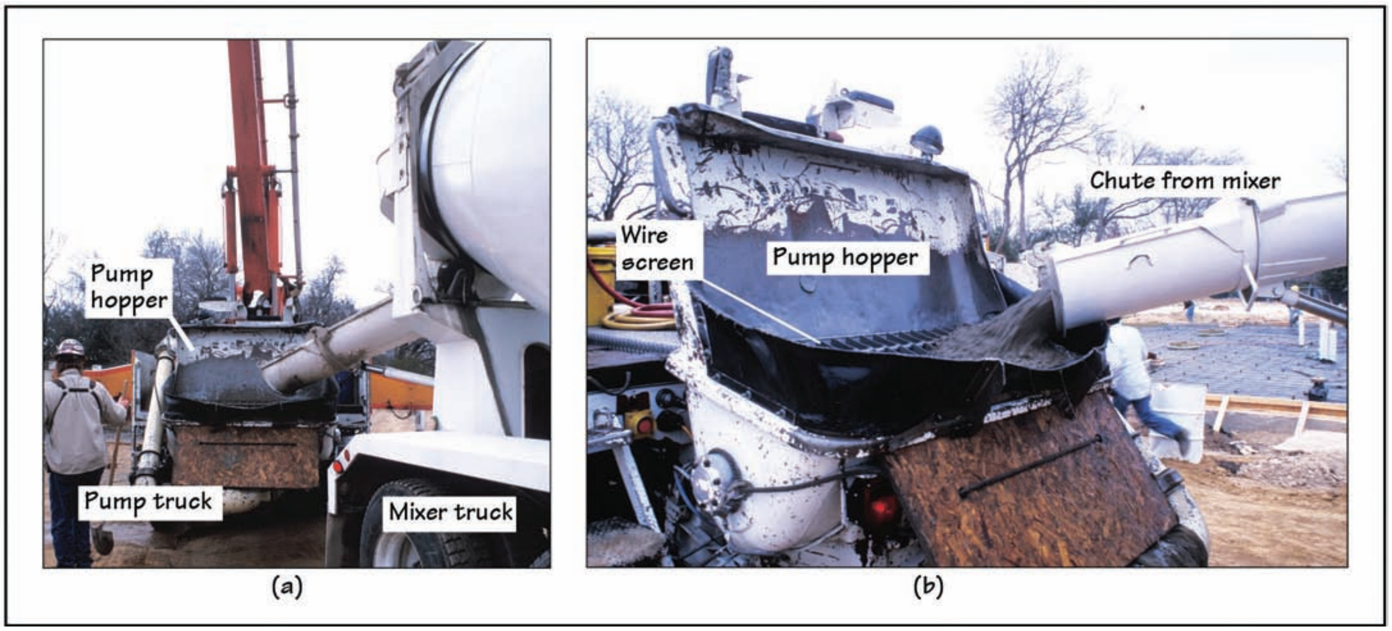

Pump truck
Concrete's destination
Mixer truck

FIGURE 21.26 Pumping of concrete from a mixer truck into a pump truck and then to the final destination, which, in this case, is a second-floor slab.


Pump hopper
Pump truck
Mixer truck
Wire screen
Pump hopper
Chute from mixer

(a)

(b)

FIGURE 21.27 **(a)** Concrete being transferred from a mixer truck to the hopper of a pump truck. **(b)** Details of the pump hopper, which has a wire screen to arrest any undesirable element in concrete that may clog the pump or the pipeline.

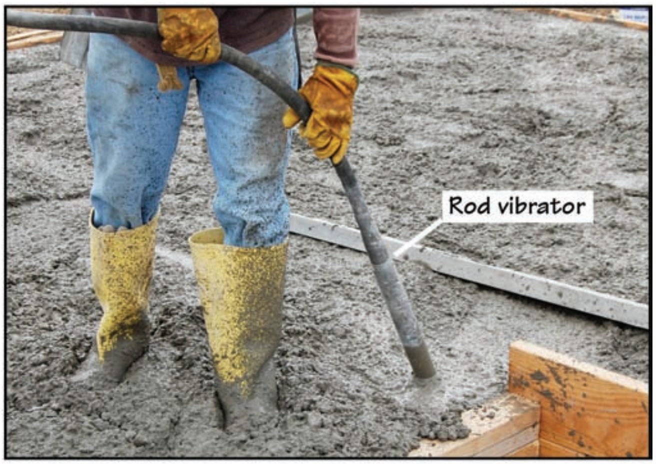

Rod vibrator

FIGURE 21.28 Consolidation of concrete using a power-driven rod vibrator.

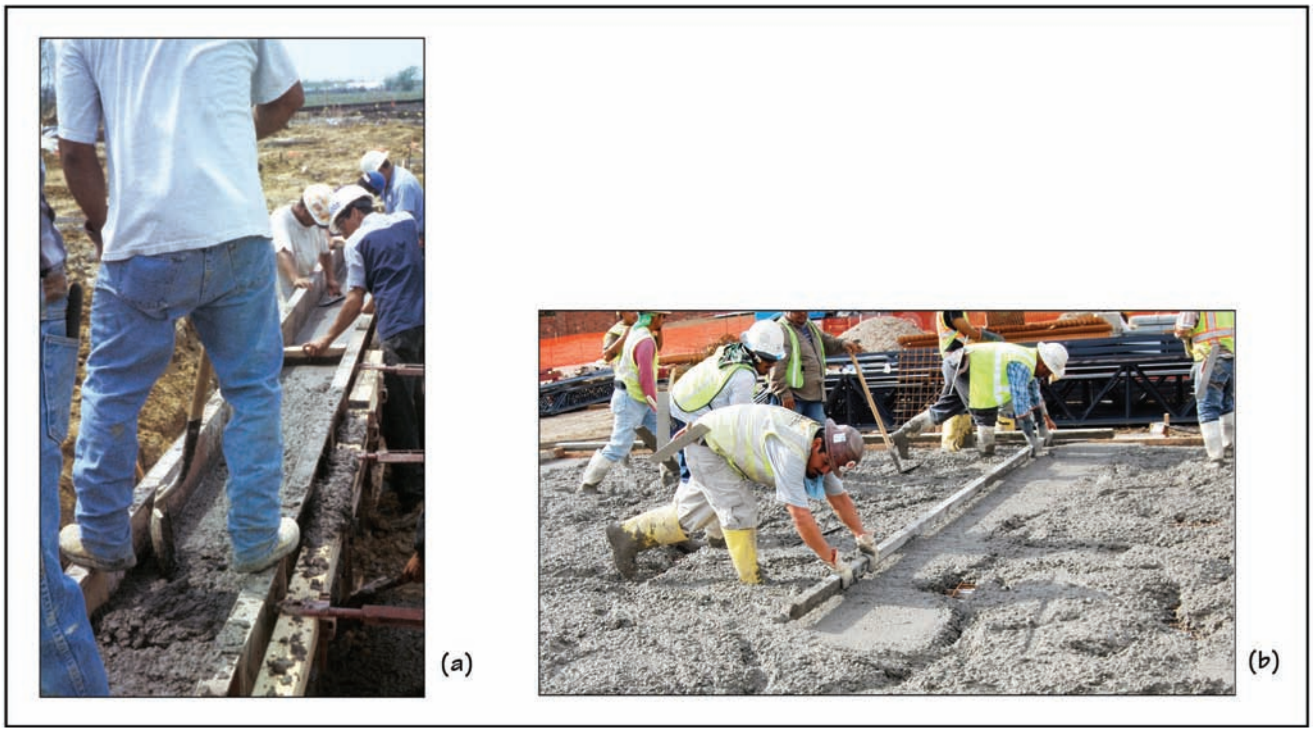
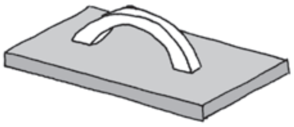


FIGURE 21.29 **(a)** Striking of concrete in a beam with a wood straight edge. **(b)** Striking of concrete in a slab with a metal straight edge.

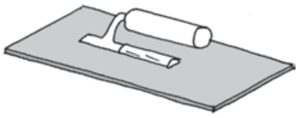
The purpose of strike off (also called *striking* or *screeding*) is to level the concrete surface. It is done with a wood straightedge, generally a 2 × 4 member, Figure 21.29. The straightedge removes excess concrete as it is moved from one point to another. It also achieves some surface compaction. Low spots behind the straight edge are filled using a shovel or hand trowel, and high spots are struck off.

Immediately following the strike off operation, a concrete surface is floated. Floating (also called *darbying*) is usually done by a hand float or a bull float, which smoothes the surface further, Figure 21.30. For non-air-entrained concrete, floats are usually made of wood. For air-entrained concrete, they are generally made of aluminum or magnesium alloys.

Striking and floating are the only operations needed for most concrete that does not require any additional finishing. However, an interior concrete slab that is to be covered with a carpet or thin floor tiles must be troweled to achieve a smooth surface. Troweling is done after the concrete has stiffened somewhat (reached its initial set point), which may be an hour or longer after floating, depending on the ambient temperature. (A general rule of thumb is that concrete should sustain foot pressure with a maximum $\frac{1}{4}$-in.-indentation before beginning troweling.) Troweling may be done using a hand trowel, which consists of a steel plate attached to a wood handle, or by a power-driven rotary trowel, Figure 21.31. Where a rough surface is required, troweling is replaced by brooming. This is achieved through the use of steel wire brooms or fiber brooms.



A typical hand float



A typical hand trowel

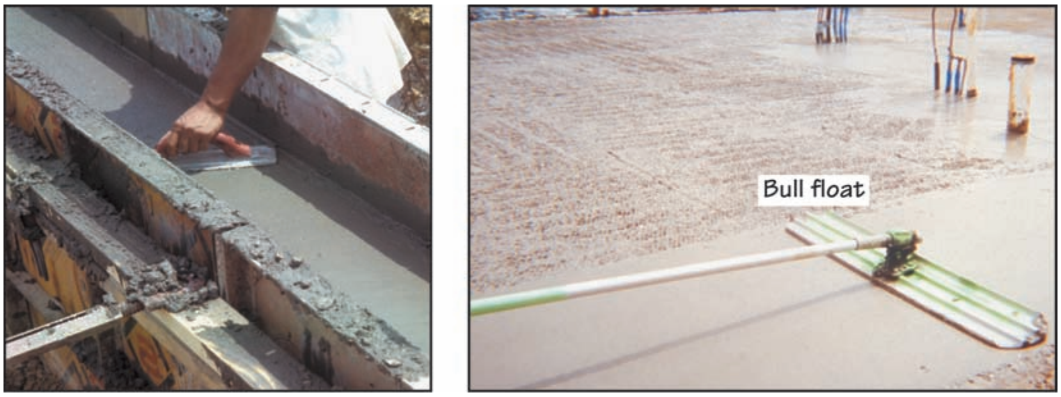


FIGURE 21.30 Floating of a small concrete surface with a hand float and a large surface with a long-handle bull float.

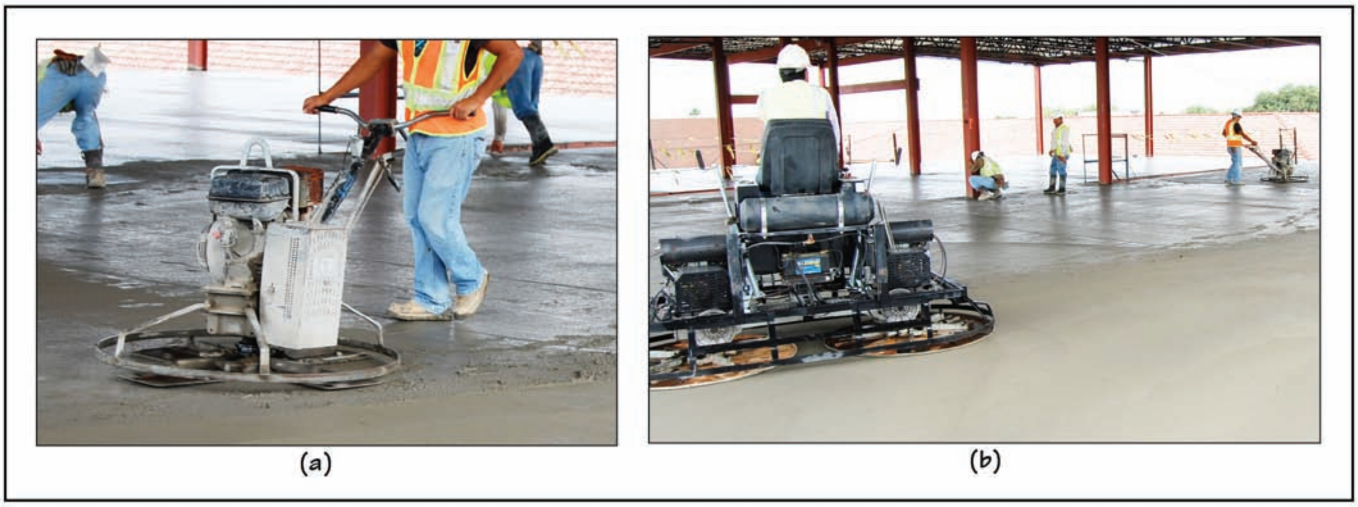


FIGURE 21.31 Troweling of concrete with power-driven troweling machines, which are available in two different types: **(a)** walk-behind troweler and **(b)** ride-on troweler. Each machine has metal blades that rotate over the concrete surface to finish it smooth.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

20. The slump of concrete is measured
- **a.** when the concrete is fresh.
- **b.** 28 days after casting the concrete in a test specimen.
- **c.** 14 days after casting the concrete in a test specimen.
- **d.** 7 days after casting the concrete in a test specimen.
- **e.** 1 day after casting the concrete in a test specimen.

21. The slump of concrete is a measure of the
- **a.** compressive strength of concrete.
- **b.** tensile strength of concrete.
- **c.** modulus of elasticity of concrete.
- **d.** workability of concrete.

22. The test specimen used for determining the compressive strength of concrete in the United States is a
- **a.** 6-in. diameter, 6-in.-high cylinder.
- **b.** 6-in. diameter, 12-in.-high cylinder.
- **c.** 6-in. diameter, 18-in.-high cylinder.
- **d.** 6-in. diameter, 12-in.-high cone.

23. The compressive strength of concrete is generally measured
- **a.** when the concrete is fresh.
- **b.** 28 days after casting the concrete in a test specimen.
- **c.** 14 days after casting the concrete in a test specimen.
- **d.** 7 days after casting the concrete in a test specimen.
- **e.** 1 day after casting the concrete in a test specimen.

24. In a high-rise building, the concrete may be brought from the ground to the location of placement by
- **a.** chutes.
- **b.** buckets.
- **c.** pumping.
- **d.** (a) or (b).
- **e.** (b) or (c).

25. After concrete has been placed in the form, it should be consolidated as much as is economically practical.
- **a.** True
- **b.** False

26. The consolidation of concrete on a construction site are generally done
- **a.** manually using a 2-in.-diameter, 3-ft-long steel rod.
- **b.** manually using a 1-in.-diameter, 3-ft-long steel rod.
- **c.** using a power-driven rod vibrator.
- **d.** using a power-driven plate vibrator.

27. The finishing operations of a concrete surface usually involve striking, floating, and troweling. The sequence in which these three operations are generally performed is
- **a.** striking, floating, and troweling.
- **b.** floating, striking, and troweling.
- **c.** striking, troweling, and floating.
- **d.** troweling, floating, and striking.

21.9 PORTLAND CEMENT AND WATER REACTION

Concrete and other mixes made from Portland cement gain their strength due to the reaction of Portland cement with water, referred to as the *hydration of Portland cement*. The amount of water required for complete hydration is about 40% of the weight of Portland cement. In other words, for complete hydration, the water-cement ratio (referred to as the *w-c ratio*) should be 0.40. Often, however, a larger quantity of water is needed to provide the requisite workability of concrete.

To obtain a normal-weight concrete with a slump of 4 in. or so (used for beams and columns), a w-c ratio of 0.55 to 0.6 is usually needed, which exceeds that needed for complete hydration. In some concretes, the w-c ratio required may be as high as 0.7. The excess water eventually evaporates, leaving air voids in hardened concrete, which reduce concrete's strength.

Experiments have indicated that the strength of concrete is inversely proportional to the w-c ratio, Figure 21.32. Therefore, a concrete should contain the minimum amount of water that gives it the required workability.

DURATION OF HYDRATION REACTION—THE CURING OF CONCRETE

The hydration reaction begins as soon as water and Portland cement come into contact, but the rate at which this reaction proceeds is extremely slow. It takes up to six months or longer

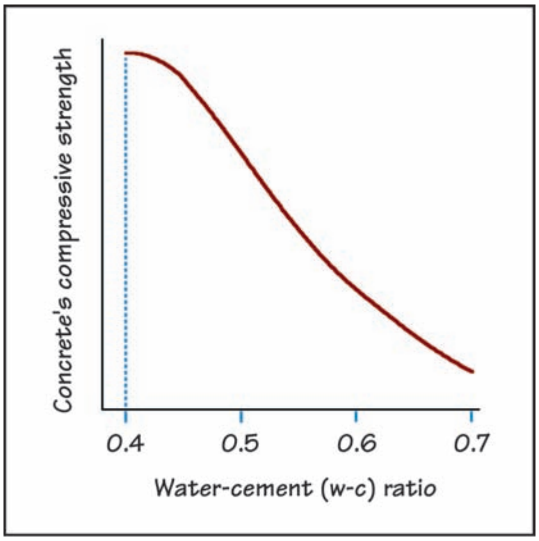


FIGURE 21.32 Strength of concrete as a function of the w-c ratio. For a given concrete (type of aggregate and amount of Portland cement), concrete's strength increases as the amount of water used is reduced.

for concrete to gain its full strength, Figure 21.33. However, approximately 80% of concrete strength develops in 28 days.

Approximately two-thirds of the 28-day strength is obtained in the first 7 days and approximately half in the first 3 days. This is true only if sufficient water and favorable temperature are available for the hydration reaction to continue. That is why concrete test cylinders are kept in a moist chamber until tested. Providing moisture to concrete continuously for hydration is called *curing of concrete*.

Curing not only increases the strength of concrete, but also reduces its permeability to water. A well-cured concrete is denser and, hence, stronger and more durable. On construction sites, curing is begun as soon as the concrete has fully set (solidified), which is generally 12 h to 24 h after placing the concrete. Curing in the initial stages of hardening is extremely important and should continue as long as possible, not less than seven days. The following methods of field curing are common:

- *Keeping concrete wet with water*: This is the most effective curing method, which includes covering the exposed surfaces of concrete with water-absorptive materials, such as burlap cloth, rags, or blankets, and sprinkling water on them, Figure 21.34. If it is possible to continuously sprinkle water on concrete, cover materials are not necessary.

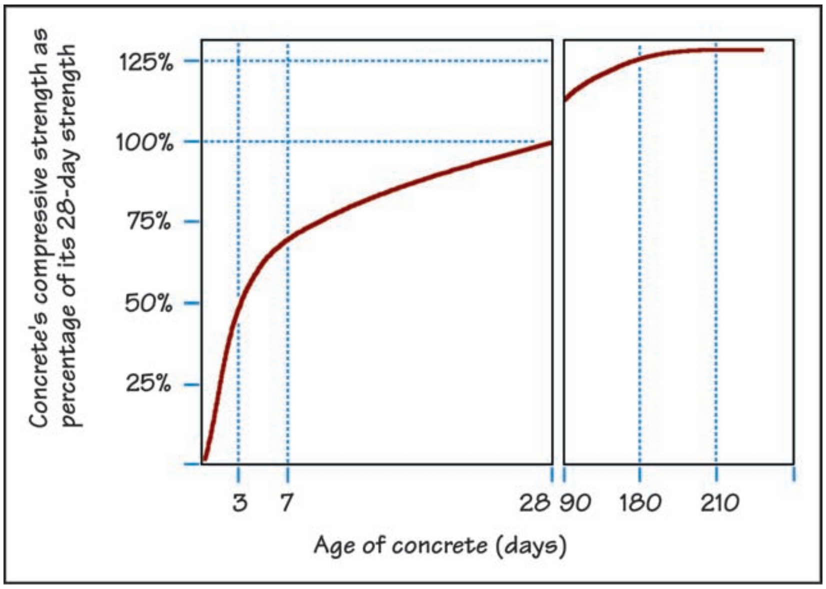


FIGURE 21.33 Compressive strength of concrete as a function of its age. Observe that concrete keeps gaining strength well beyond 28 days. Since we generally use concrete's 28-day strength as the design strength, the additional strength adds to the safety of a concrete structure.

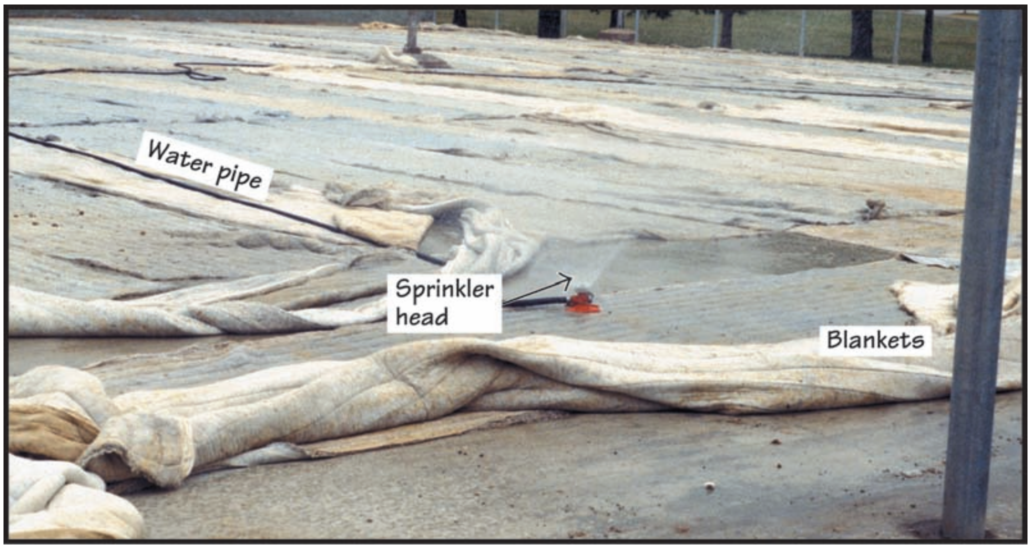


FIGURE 21.34 Curing of a recently placed concrete slab-on-ground. Notice the blankets, water pipe, and sprinkler.

- *Covering concrete with a plastic sheet:* Because concrete usually has more water than needed, covering concrete with a plastic sheet retains its moisture. However, in warm and (or) windy climates, where the evaporation of water is rapid, this method alone is not adequate.
- *Using curing compounds:* This consists of spraying concrete with a liquid membrane. A liquid membrane is like a plastic sheet. However, it becomes an integral part of the concrete surface. If the concrete is to receive a subsequent surface treatment, such as a floor or other finish that requires bonding with concrete, curing compounds should not be used. Curing compounds are often used on street pavements and bridge decks, which do not have a source of continuous water supply available.

INFLUENCE OF TEMPERATURE ON HYDRATION

Hydration of Portland cement is temperature sensitive. The rate of hydration increases as the ambient air temperature increases, and vice versa. Below 55°F (13°C), the rate of hydration decreases significantly. The use of Type III Portland cement is helpful under these circumstances. However, low-temperature concreting should be avoided because significant reduction in concrete strength occurs if the water in concrete freezes within a few hours of the concrete's placement (generally before it attains a compressive strength of 500 psi). That is why concrete is generally not placed if the temperature of the surrounding air is below 40°F (4.5°C) or is expected to fall below 40°F (4.5°C) within a day or so.

If concrete must be placed when the temperature is below 40°F (4.5°C), one or more of the following precautions must be taken: warming the aggregates and water, insulating the forms, surrounding the concrete in a heated enclosure, and/or using Type III Portland cement.

Special precautions are also required if concreting is to be done in hot weather—generally, if the air temperature exceeds 100°F (37.5°C). However, low humidity and windy conditions may necessitate these precautions below 100°F (37.5°C). Generally, wetting the aggregates with water to cool them evaporatively, building a protective cover to shield against direct solar radiation and wind, concreting after sunset, and using chilled water, crushed ice, or liquid air (see Figure 21.20) are some of the measures that are generally adopted.

NOTE

Key Temperature: 40°F (4.5°C) and Rising

It is common not to place concrete if the ambient air temperature is 40°F (4.5°C) and decreasing. In other words, concrete should be placed only when the ambient air temperature is at least 40°F (4.5°C) and rising, unless necessary precautions are taken to prevent damage to fresh concrete due to its freezing.

21.10 WATER-REDUCING CONCRETE ADMIXTURES

Ever since it became known that reducing the water content in concrete increases its strength, the concrete industry began to find ways of reducing the amount of water without decreasing the workability of concrete. This finally became possible with the discovery of chemicals known as *plasticizers* or, more commonly, as *water-reducing admixtures* (WRAs).

A WRA acts on the surfaces of Portland cement particles. The commonly used concrete mixes do not contain a WRA. In the absence of a WRA, the particles of Portland cement tend to cluster together. To overcome the clustering (flocculation) tendency, a larger amount of water is needed to make concrete workable. A WRA reduces flocculation and disperses cement particles in the mix so that each particle is covered with a sheath of water around it rather than the particles of cement. This provides greater lubrication, increasing workability. WRA increases concrete slump by 10% to 15%. Additionally, each cement particle, being surrounded by water, is able to hydrate more fully, which increases concrete's strength.

The discovery of WRAs led to the production and use of stronger concrete. However, the real breakthrough in producing high-strength concrete came with the discovery of superplasticizers, also known as *high-range water reducers* (HRWRs). An HRWR, which is chemically different from a WRA, works on the same principles as a WRA but reduces the water requirement substantially, up to about 30%.

The introduction of HRWRs has produced concrete strengths that were considered impossible a couple of decades ago. Concrete up to a compressive strength of approximately 50,000 psi has been produced in laboratories, and concretes with a compressive strength up to 20,000 psi has been used in buildings [Refs. 21.2 and 21.3]. This is a major leap forward, considering that until 1960, the highest concrete strength used in buildings was 5,000 psi.

21.11 HIGH-STRENGTH CONCRETE

The realization of high concrete strengths means that concrete competes with steel for the structural frame of tall buildings. Until recently, steel was the only material that could be used for buildings taller than 40 stories or so. Today, concrete is used in the structural frame of some of the tallest buildings in the world. The commonly used yield strengths of steel, 36,000 psi and 50,000 psi, are well above the (current) maximum possible concrete compressive strength of 20,000 psi. However, concrete competes favorably with steel because of its two major advantages:

- The first advantage is concrete's inherent fire resistance. Steel must be protected through an additional fire-protective treatment. A fire-protective treatment adds to the cost of a steel structure in two ways. The first cost is that of the treatment. The second cost is in the drop ceilings under the floors to conceal the protective treatment. Fire-protective treatment is unsightly, fibrous, and easily scrapable. Without a drop ceiling, loose fibers can get into the environment, with obvious health concerns.
- The second advantage of concrete over steel is that the modulus of elasticity of concrete increases with increasing strength. Steel's modulus of elasticity is constant at 29,000 ksi, regardless of steel's strength. Modulus of elasticity is an important structural property, particularly for tall buildings. Remember (Chapter 4) that the modulus of elasticity signifies the stiffness of a material. A tall building, which functions structurally as a vertical cantilever such as a flagpole, is subjected to deflection and side sway caused by wind and earthquake. Therefore, stiffness is an important requirement of the material used in a tall building.

Although the modulus of elasticity of even high-strength concrete is well below that of steel, increasing the strength of concrete gives dividends in terms of increased modulus of elasticity. This is not so for steel because of its constant modulus of elasticity. Thus, although steel is produced in strengths much higher than 50 ksi, the use of high-strength steel in the structural frames of buildings is rare.

The consequence of these facts is that the height of buildings with a concrete structural frame has progressively increased over the years, Figure 21.35. Until 1959, the tallest building with a concrete structural frame was 370 ft high, in which 5,000-psi concrete was used. In 1997, the 1,500-ft-high Petronas Towers were built in Kuala Lumpur utilizing steel-encased concrete columns with concrete strength of 20,000 psi. The Petronas Towers are taller than the steel-framed Sears Tower in Chicago. (Taller buildings, in China and Dubai are currently under construction.)

OTHER INGREDIENTS OF HIGH-STRENGTH CONCRETE

Concrete is a material that can be produced with compressive strength ranging from 2,000 psi to 20,000 psi on construction sites. This is unlike steel, which is available in two or three standard strengths. The concrete industry has, therefore, divided concrete into two classifications based on its strength:

- Conventional concrete—compressive strength $<$6,000 psi
- High-strength concrete—compressive strength $\geq$6,000 psi

NOTE

Concrete Admixtures

A concrete admixture is defined as a material other than Portland cement, coarse and fine aggregates, and water.

A commonly used concrete admixture is fly ash. An air-entraining admixture is used to increase concrete's durability against the freeze-thaw effect. It is more commonly used in concrete pavements and bridges in colder climates. The following other admixtures are used as needed:

- WRA
- HRWR
- Silica fume
- Set accelerator
- Set retarder

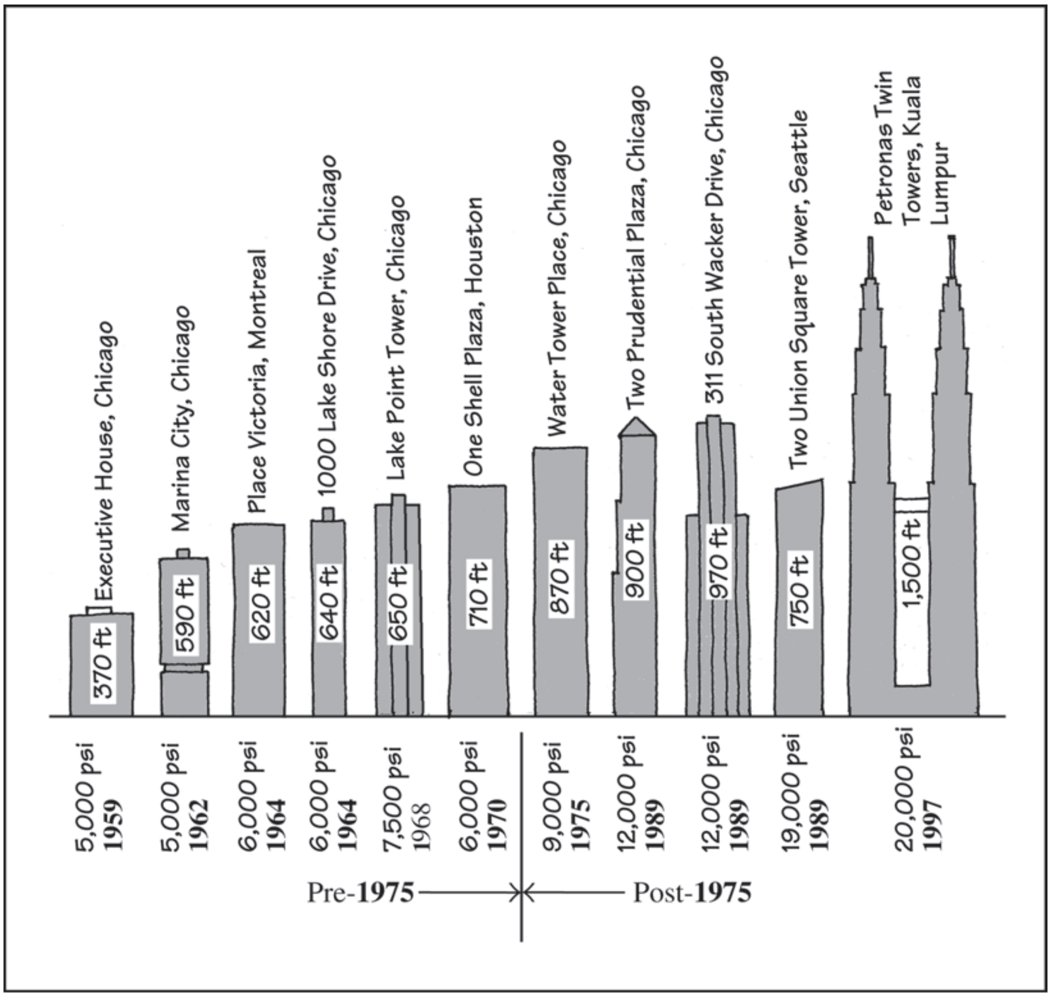


FIGURE 21.35 Progressive increase in concrete's strength in the structural frame of buildings.

This division is totally arbitrary because no one factor affects concrete strength abruptly. Generally, conventional concrete may be produced without the use of admixtures. High-strength concrete requires the use of admixtures. A *concrete admixture* is defined as a material other than Portland cement, coarse and fine aggregates, and water. WRAs and HRWRs are not the only materials required for the production of high-strength concrete. High-strength concrete also requires the use of other admixtures, such as fly ash and silica fume.

FLY ASH—A SUSTAINABLE CONCRETE INGREDIENT

As mentioned previously, fly ash is a waste product produced by coal-fired power stations. It is used in both high-strength and conventional concretes. Because fly ash particles are microscopic in size, they densify concrete, filling in voids between Portland cement particles. The densification of concrete increases its strength and durability. Small particles of fly ash also increase concrete's workability and reduce the permeability and creep of concrete (Section 9.6).

However, the main benefit of fly ash is in its pozzolanic property. During the manufacture of Portland cement, a certain amount of lime (calcium hydroxide) does not convert to complex Portland compounds—alite, belite, celite, and so on. This lime is referred to as *free lime*. Fly ash reacts with free lime, converting it into a hydraulic cement, and adds to concrete's strength.

SILICA FUME—A SUSTAINABLE CONCRETE INGREDIENT

Silica fume is a waste product from the silicon industry. It is an extremely fine and amorphous silica (sand) with average particle size of 0.1 μm [21.4]. In other words, more than 100 silica fume particles occupy the same space as 1 particle of Portland cement. Silica fume fills the voids that other concrete materials cannot. It is an extremely lightweight material and is available in bags, Figure 21.36. A large silica fume bag weighs less than 10 lb. Silica fume is an expensive concrete admixture. Therefore, it is not commonly used in conventional concrete. It has excellent pozzolanic properties. Like fly ash, it reacts with free lime to convert it into a hydraulic cement.

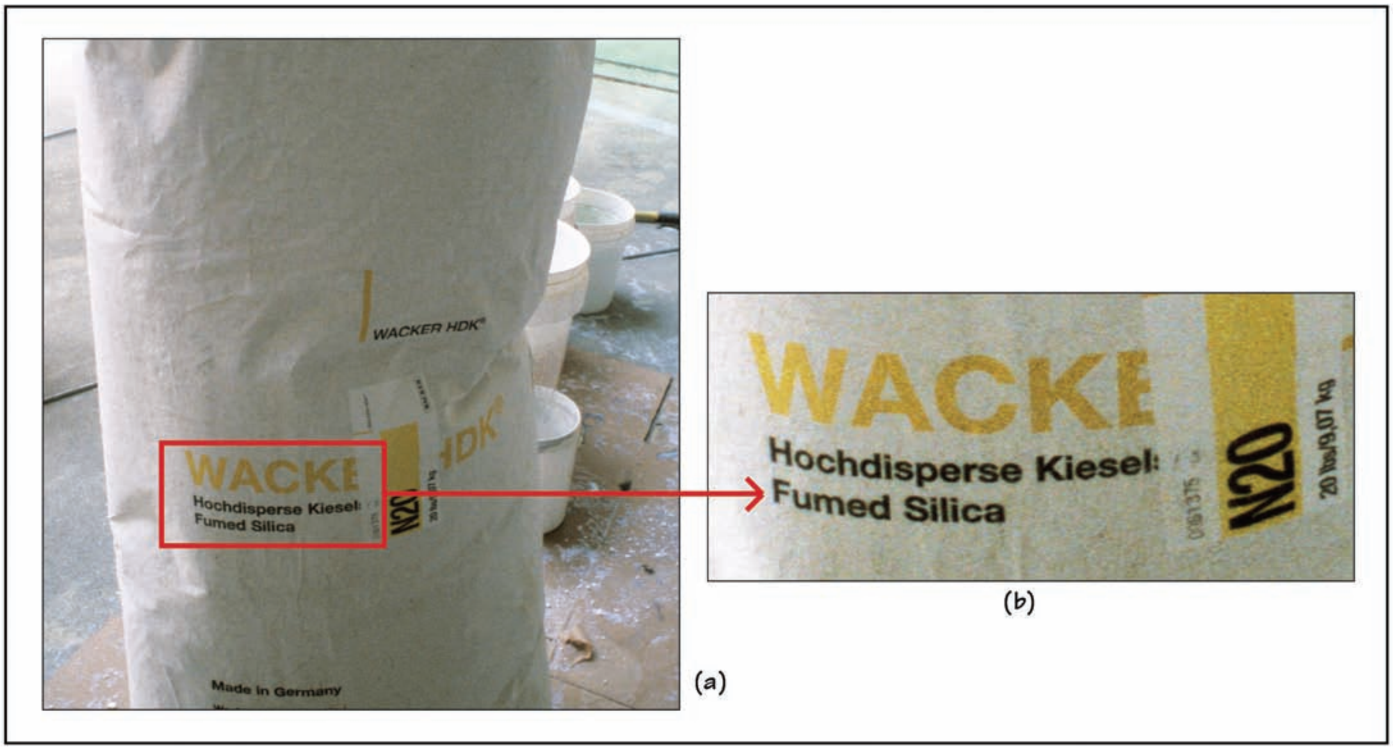


FIGURE 21.36 A silica fume bag, so light weight that a 2-ft-diameter 4-ft-tall bag can be easily lifted with one hand.

HIGH-STRENGTH CONCRETE AND PORTLAND CEMENT QUANTITY

Because Portland cement is the binding agent, its contribution to concrete's strength is obvious. In general, the greater the amount of Portland cement, the greater the concrete's strength. However, increasing the amount of Portland cement in a mix yields exponentially smaller increases in its strength. In general, more than 900 lb (approximately 10 bags) of Portland cement per cubic yard does not increase concrete's strength significantly.

DISADVANTAGES OF HIGH-STRENGTH CONCRETE

The cost of concrete increases with increasing strength. At 20,000 psi or so, the mix is not only very expensive but requires a great deal of quality control at the site, which increases the cost further. Remember, concrete's strength depends on the quality of aggregates and admixtures, grading of aggregates, and the quantity of Portland cement. It also depends on placing, compacting, and curing. An ultra-high-strength concrete requires that all of these factors be very tightly controlled.

21.12 STEEL REINFORCEMENT

Concrete is much weaker in tension than in compression. Its tensile strength is approximately 10% of its compressive strength. Therefore, concrete is generally used in conjunction with steel reinforcement, which provides the tensile strength in a concrete member. The use of plain concrete—concrete without steel reinforcement—is limited to pavements and some slabs-on-ground.

Steel is the ideal material to complement concrete because the thermal expansion of both materials is the same. In other words, when heated or cooled, both steel and concrete expand or contract equally. Consequently, no stress is caused by differential expansion or contraction. Composite materials that expand differentially are subjected to such stresses.

Steel also bonds well with concrete. In a composite material, the bond between two materials is necessary for it to function as a single material. The bond between steel and concrete is due to the chemistry of the two materials, which produces a *chemical bond* between them. Additionally, as water from concrete evaporates, it shrinks and grips the steel bars, making a *mechanical bond.*

The mechanical bond is enhanced by using reinforcing bars, or *rebar*, that have surface deformations, Figure 21.37. Because a mechanical bond is a function of the area of contact between the two materials, surface deformations increase that area, thereby increasing the bond. For the same reason, rebar that have a light, firm layer of rust bonds better with concrete. Rust that is produced by leaving rebar outdoors on a construction site for a few days or weeks is not objectionable as long as the rust

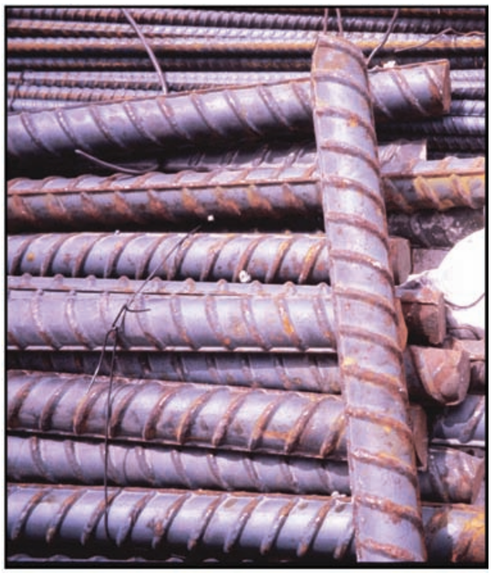


FIGURE 21.37 Surface deformations on concrete reinforcing bars.

is not loose or flaky. Loose and flaky rust should be scraped using burlap or a piece of cloth. Excessively rusted rebar should not be used.

Virtually all reinforcement in a concrete member consists of deformed bars. Plain (smooth, undeformed) bars are used only as dowels at expansion joints. At expansion joints, rebar are oiled (or covered with a sleeve) before being embedded in concrete to allow movement at the joint. This requires the use of plain bars. Plain rebar are also used as spiral reinforcement in round columns.

REINFORCING STEEL GRADE

As we learned in Chapter 4, yield strength is an important steel property. Rebar are hot rolled from steels of the following yield strengths:

- 40,000 psi—referred to as *grade 40 steel*
- 60,000 psi—referred to as *grade 60 steel*

The cost of both steel grades is approximately the same. Grade 60 steel is one-and-a-half times stronger than grade 40 steel. Therefore, it is by far the most frequently used steel grade. Grade 40, which is more ductile, that is, more easily bendable, is used where rebar need to be field bent. Grade 50 is also available but is rarely used.

DIAMETER AND LENGTH OF BARS

Eleven different diameters of rebar are available, from $\frac{3}{8}$ in. to $2\frac{1}{4}$ in., Table 21.3. The diameter of a bar is generally stated in terms of a number. Thus, a No. 3 bar (commonly stated as a #3 bar) has a diameter of $\frac{3}{8}$ in. A #4 bar has a diameter of $\frac{1}{2}$ in., a #5 bar has a diameter of $\frac{5}{8}$ in., and so on, up to a #8 bar, which has a diameter of 1 in.

According to this numbering system, a #9 bar should have a diameter of $\frac{9}{8}$ in. (1.125 in.). However, its actual diameter is 1.128 in., providing a cross-sectional area of 1.0 in.^{2}. In structural calculations, the cross-sectional area of a bar is more important than the bar diameter. Therefore, rationalizing area is more important than the diameter. That is why a #18 bar has a diameter of 2.257 in., which gives an area of 4.0 in.^{2}. Note that $\frac{18}{8} = 2.25$.

Deformed rebar are available from #3 up. A $\frac{1}{4}$-in.-diameter bar is available only as a plain bar, but it is not used as concrete reinforcement except in welded wire reinforcement, as described later. The diameter of a deformed bar is its nominal diameter. The nominal diameter is the diameter that gives the same cross-sectional area as a plain bar.

Bar lengths of 20 ft and 40 ft are standard stock sizes. Lengths up to 60 ft are generally available as special orders. The 60-ft length is based more on transportation limitations than on manufacturing.

BAR IDENTIFICATION MARKINGS

Each rebar in the United States carries an identification marking, Figure 21.38. The marking consists of four pieces of information in the following order:

- Producing mill's identification number or symbol.
- Type of steel. The most commonly used steel is new billet steel. Its identification mark is *N*. Mark *S* is used for special billet steel. Mark *R* is used for rail steel. Some mills close to old, unused rail lines produce this steel. Mark *A* stands for axle steel.

TABLE 21.3 STANDARD BAR DIAMETERS AND AREAS

Bar size and designation	Diameter (in.)	Cross-sectional area (in.^{2})
#3	0.375	0.11
#4	0.500	0.20
#5	0.625	0.31
#6	0.750	0.44
#7	0.875	0.60
#8	1.000	0.79
#9	1.128	1.00
#10	1.270	1.27
#11	1.410	1.56
#14	1.693	2.25
#18	2.257	4.00

- Bar size.
- Steel grade. Each bar carries at least two vertical lines. These are simply deformation lines. An additional vertical line on a bar is the grade line, implying that it is grade 60 bar. No grade line means that it is grade 40 or 50 bar. Bars that have diagonal deformations have the grade stamped on them during manufacturing if they are of grade 60. No grade stamp means a grade 40 or 50 bar.

BENDING AND TYING OF BARS

In a concrete member (beam, slab, or column), some rebar need to be straight, and others need to be bent to required profiles. The cutting and bending of rebar is done in a rebar fabrication plant. Rebar arrive at a construction site prebent and in the required lengths, Figure 21.39. Rebar bundles arrive at the construction site with identification tags that identify the structural members to which the bars belong.

After the bars are received at the site, they are assembled in beam-and-column cages. The cage assembly requires tying the bars together, Figure 21.40. Tie wires are approximately $\frac{1}{20}$-in.-diameter steel wires, which can be easily bent with the hands.

EPOXY-COATED BARS

Most reinforcing bars in concrete members are black bars, that is, they do not have any surface coating. However, concrete members that are exposed to corrosive atmospheres require coated bars. Fusion-bonded, epoxy-coated bars are commonly used in concrete bridges and parking garages exposed to deicing salts, which gradually penetrate through concrete to corrode the bars. Epoxy-coated bars may also be used in other corrosive atmospheres.

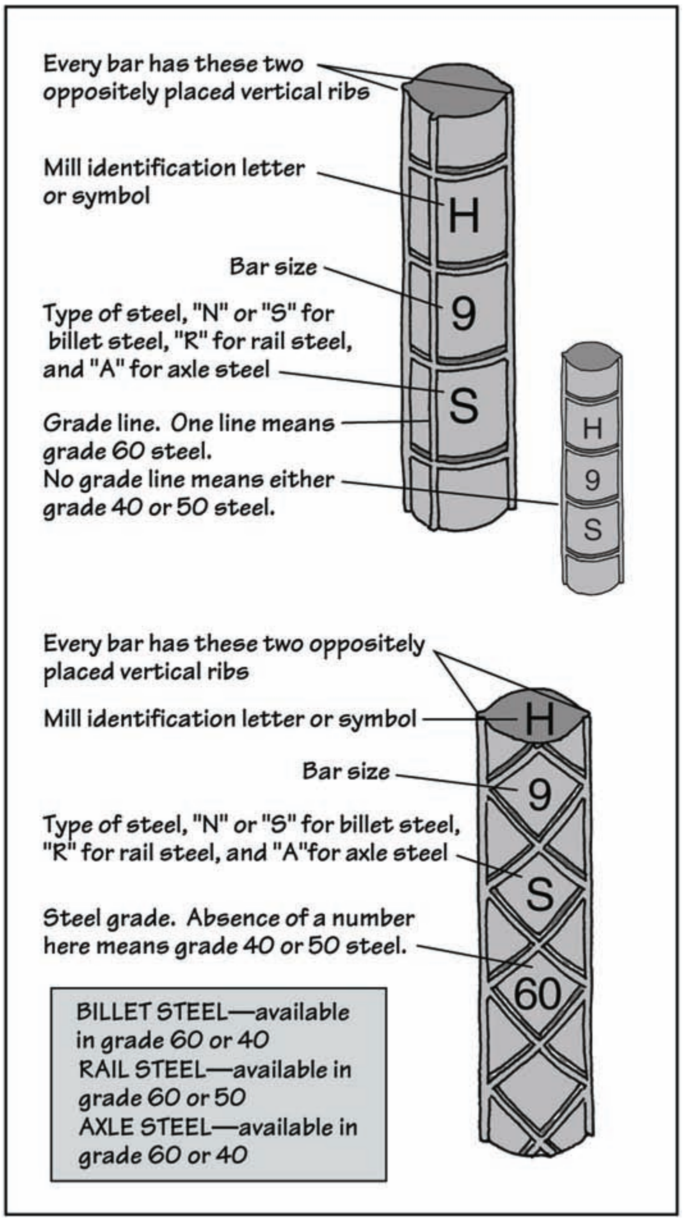

Every bar has these two oppositely placed vertical ribs
Mill identification letter or symbol
H
Bar size
9
Type of steel, "N" or "S" for billet steel, "R" for rail steel, and "A" for axle steel
S
Grade line. One line means grade 60 steel.
No grade line means either grade 40 or 50 steel.
H
9
S
Every bar has these two oppositely placed vertical ribs
Mill identification letter or symbol
H
Bar size
9
Type of steel, "N" or "S" for billet steel, "R" for rail steel, and "A"for axle steel
S
Steel grade. Absence of a number here means grade 40 or 50 steel.
60
BILLET STEEL—available in grade 60 or 40
RAIL STEEL—available in grade 60 or 50
AXLE STEEL—available in grade 60 or 40

FIGURE 21.38 Two commonly used identification markings on reinforcing bars.

21.13 WELDED WIRE REINFORCEMENT (WWR)

Welded wire reinforcement (WWR) is a prefabricated reinforcing steel available in rolls or mats, Figure 21.41. Rolls come in widths of 5 ft to 7 ft. Mats come in various dimensions. They are commonly used in ground-supported slabs (or pavement) and steel deck–supported slabs, where reinforcement requirements are marginal, that is, much smaller than those needed for reinforced concrete suspended slabs.

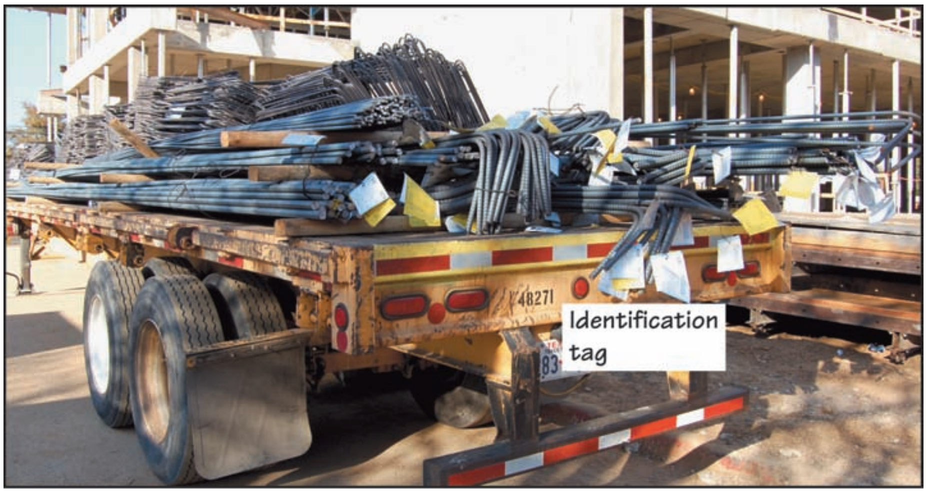

Identification tag

FIGURE 21.39 Bars generally arrive at a construction site bent to shape and cut to required lengths. Tags attached to the bundles identify the building component (beam, column, or slab) to which the bars belong.

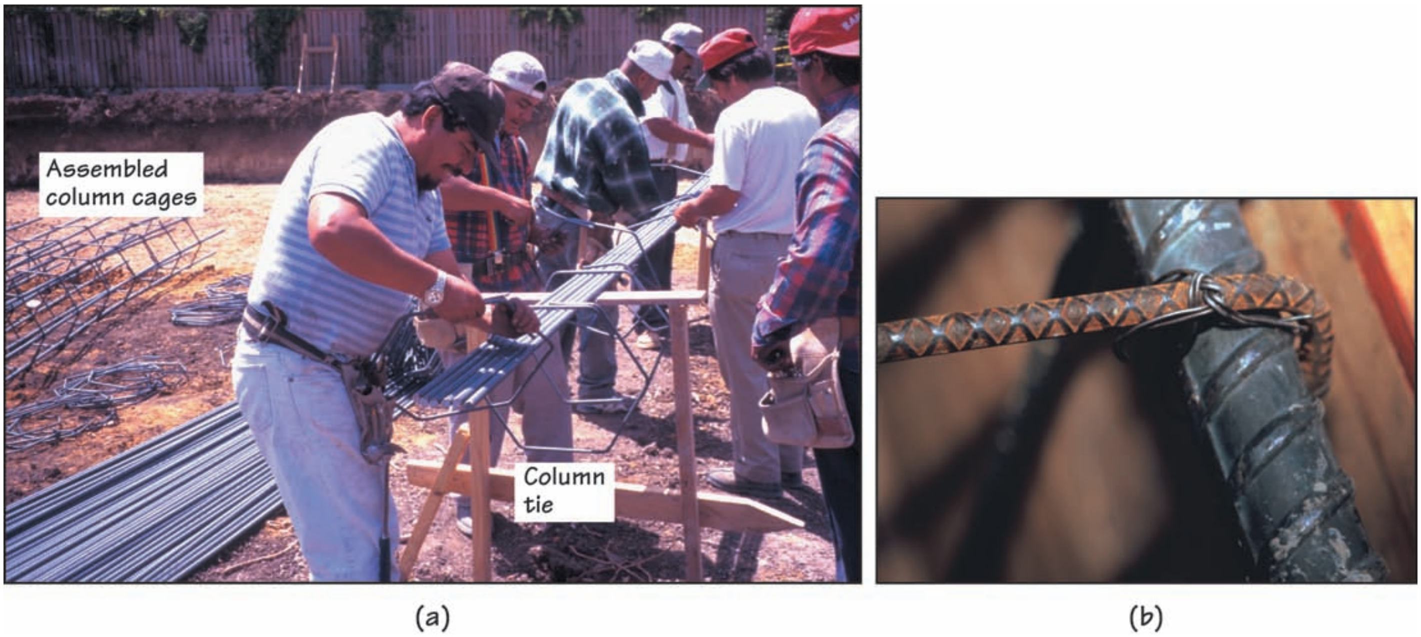


FIGURE 21.40 **(a)** Bars are assembled into cages at construction site, which requires tying the bars together with a steel wire. Assembled cages are seen in the background. **(b)** Close-up of tied bars showing the wire.

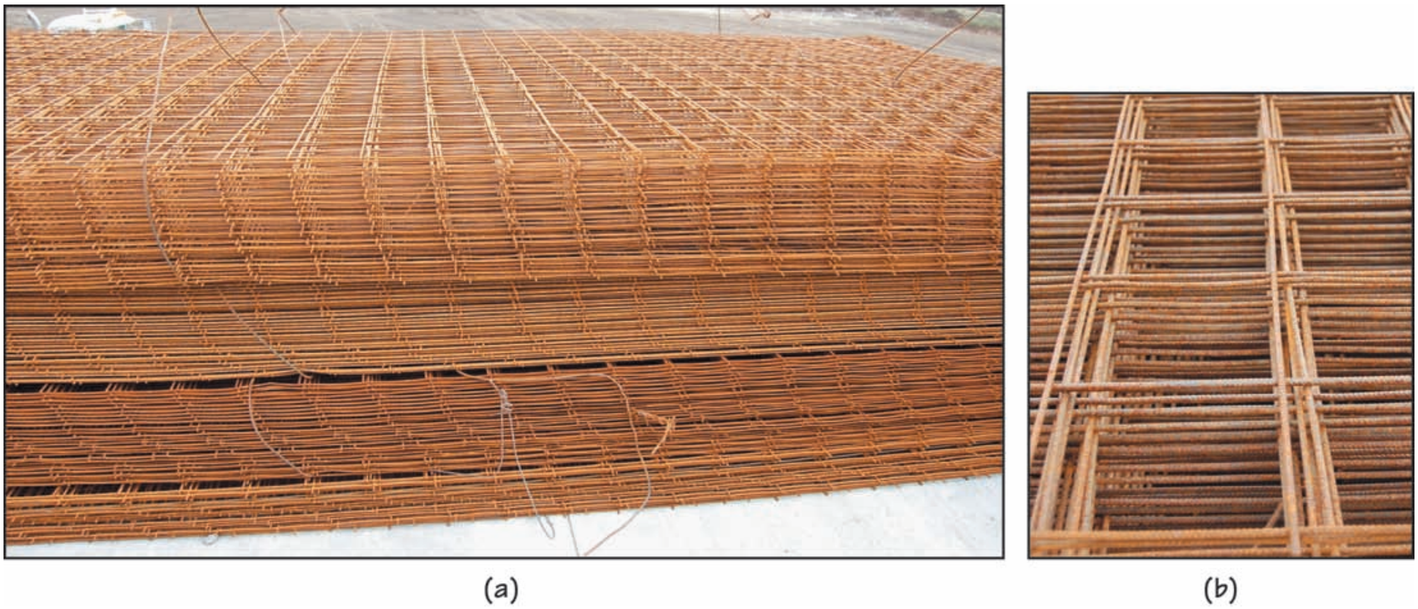


FIGURE 21.41 **(a)** A stack of welded wire reinforcement (WWR) matts. **(b)** Close-up of WWR.

A WWR roll or matt consists of a rectangular mesh of steel wires. Longitudinal wires are spot welded to transverse wires at each intersection. If conventional rebars are used in place of a WWR, each bar would need to be tied manually at intersections. The use of WWR greatly speeds reinforcement assembly at the site.

DESIGNATION OF A WWR ROLL OR MAT

Both plain and deformed bars are used in a WWR in steel grades of 40 and 60. A WWR roll or mat is designated by either *W* or *D*, implying the use of plain wires or deformed wires, respectively. Additional designation includes the cross-sectional areas of wires and their spacing.

For example, WWR designated as 6 × 8-W2.9 × W2.9 means that the longitudinal wires are spaced 6 in. on center, and the transverse wires are at 8 in. on center. *W* indicates plain wires, and the cross-sectional area of the longitudinal and transverse wires is 2.9/100, that is, 0.029 in.^{2}. A designation of 6 × 6-D4.0 × D4.0 means that it is a fabric consisting of deformed wires spaced 6 in. on center in both directions. The wires have a cross-sectional area of 0.04 in.^{2}.

FOCUS ON SUSTAINABILITY

Sustainability Considerations in Concrete

Like other materials, concrete has a few inherent sustainability features, which include durability, easy recycling, use of waste materials from other industries, no VOC emissions, and high surface reflectivity of the finished material.

Durability

Concrete does not burn, corrode, or decay. Consequently, it is a durable material and, hence, environmentally responsible. Concrete foundations, floor slabs, structural frame members, roads, and pavements last a long time.

Recycling

Concrete obtained from old, demolished buildings and other structures can be broken or crushed and can then be used as aggregate in subgrade bases under building foundations, slabs-on-ground, roads, and pavements.

Use of Waste Materials

Most modern concrete utilizes fly ash, which is a waste product obtained from the manufacture of steel.

VOC Emissions

Concrete does not emit any volatile organic compounds (VOC), unlike plywood, OSB, synthetic carpet, and so on.

High Surface Reflectivity

Compared to several other materials, a concrete surface has reflectivity. Therefore, roads and pavements built out of concrete contribute less to the urban heat island effect than asphalt roads and pavements.

Portland Cement and Sustainability

Two major criticisms of concrete are the amount of energy used and the amount of carbon dioxide released in the production of Portland cement. In recognition of this fact, the industry is embracing initiatives that will make the manufacturing process more environmentally friendly.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

28. Portland cement sets and gains strength by virtue of its chemical reaction with
- **a.** water.
- **b.** oxygen in air.
- **c.** carbon dioxide in air.
- **d.** aggregates.
- **e.** none of the above.

29. The rate at which concrete gains strength increases as the ambient air temperature increases.
- **a.** True
- **b.** False

30. High-strength concrete is defined as concrete whose compressive strength is greater than or equal to
- **a.** 4,000 psi.
- **b.** 5,000 psi.
- **c.** 6,000 psi.
- **d.** 8,000 psi.
- **e.** 10,000 psi.

31. A high-strength concrete generally requires a
- **a.** water-increasing agent.
- **b.** water-reducing agent.
- **c.** sand-reducing agent.
- **d.** sand-increasing agent.

32. Steel reinforcing bars, generally used in concrete, have a yield strength of
- **a.** 60 ksi.
- **b.** 80 ksi.
- **c.** 100 ksi.
- **d.** 120 ksi.

33. A #8 reinforcing bar has a diameter of
- **a.** $\frac{1}{8}$ in.
- **b.** 8 in.
- **c.** 1 in.
- **d.** none of the above.

34. In a welded wire fabric mat that has a designation of 8 × 8-D4.0 × 4.0, the number 4.0 indicates that the wires are
- **a.** deformed wires, each with a diameter of 4.0 mil.
- **b.** deformed wires, each with a diameter of 0.04 in.
- **c.** deformed wires, each with a cross-sectional area of 0.04 in.^{2}.
- **d.** deformed wires, each with a cross-sectional area of 0.4 in.^{2}.
- **e.** deformed wires, each with a cross-sectional area of 4.0 in.^{2}.

35. Epoxy-coated bars are generally used in
- **a.** high-rise buildings built in warm climates.
- **b.** parking garages built in warm climates.
- **c.** high-rise buildings built in cold climates.
- **d.** parking garages built in cold climates.
- **e.** none of the above.

REVIEW QUESTIONS

1. Describe the difference between quicklime and slaked lime.
2. Describe how lime-sand mortar hardens and functions as cement.
3. List various types of Portland cement and where they are typically specified.
4. What is air-entrained Portland cement? Where is it typically specified?
5. What is lightweight structural concrete? How does it differ from normal-weight concrete? What are the advantages and disadvantages of using lightweight structural concrete?
6. With the help of a sketch, explain how the slump of concrete is determined.
7. Using sketches, explain how the compressive strength of concrete is determined.
8. Discuss the importance of the water-cement ratio in concrete.
9. Explain what curing of concrete is, and why it is necessary.
10. What is a concrete admixture, and why is it used? Discuss the commonly used concrete admixtures.

CHAPTER 22

Concrete Construction–I (Formwork, Reinforcement, and Slabs-on-Ground)

CHAPTER OUTLINE

22.1 VERSATILITY OF REINFORCED CONCRETE

22.2 CONCRETE FORMWORK AND SHORES

22.3 FORMWORK REMOVAL AND RESHORING

22.4 ARCHITECTURAL CONCRETE AND FORM LINERS

22.5 PRINCIPLES OF REINFORCING CONCRETE

22.6 SPLICES, COUPLERS, AND HOOKS IN BARS

22.7 CORROSION PROTECTION OF STEEL REINFORCEMENT

22.8 REINFORCEMENT AND FORMWORK FOR COLUMNS

22.9 REINFORCEMENT AND FORMWORK FOR WALLS

22.10 TYPES OF CONCRETE SLABS

22.11 GROUND-SUPPORTED, ISOLATED CONCRETE SLAB

22.12 GROUND-SUPPORTED, STIFFENED CONCRETE SLAB

As stated in Chapter 21, concrete is weak in tension. On average, the tensile strength of concrete is 10% of its compressive strength. The low tensile strength of concrete is offset by combining it with steel, which is strong in tension. In this concrete-steel combination, steel is fully embedded in the concrete so that both concrete and steel function integrally.

Plain concrete (i.e., concrete without steel reinforcement) may be used only in situations where tensile stresses are minimal, such as in pavements, ground-supported slabs, and lightly loaded wall footings on stable, uniformly compacted soils. Even in these situations, a nominal amount of steel is desirable to resist the tensile stresses caused by the shrinkage of concrete or unforeseen bending. There are two ways in which steel is used to strengthen concrete.

REINFORCED CONCRETE

In one option, steel reinforcing bars (rebars), discussed in Chapter 21, are used. In most concrete members subjected to bending (e.g., beams and slabs), reinforcing bars are positioned in locations where tensile stresses are likely to be produced. Because steel is also much stronger than concrete in compression, reinforcing bars are also used to provide compressive strength (e.g., in concrete columns, walls, and some beams).

A concrete member containing reinforcing bars is called a *reinforced-concrete member*. If an entire structure consists of reinforced-concrete members, which is fairly common, the structure is referred to as a *reinforced-concrete structure*.

PRESTRESSED CONCRETE

The alternative to the use of reinforcing bars is to introduce a permanent initial compression in a concrete member, giving a *prestressed concrete member*. The compression is introduced in regions of the member where tension is expected to be produced by the loads. The magnitude of compression produced by prestressing is controlled to ensure that it reduces or cancels the tension created by the loads.

Prestressing of a member is obtained using prestressing cables called *strands*, which are made of high-strength steel wires. The most commonly used strands have a yield strength of 270 ksi, which is 4.5 times stronger than the most commonly used reinforcing bars (Grade 60 steel; see Chapter 21). Prestressing can be accomplished in two ways:

- Pretensioning
- Posttensioning

In pretensioning, the strands are tensioned between two fixed abutments using hydraulic jacks, Figure 22.1. Subsequently, concrete is cast in the form enclosing the tensioned strands and allowed to cure, creating a bond between the strands and concrete. When the concrete has developed sufficient strength, the strands are cut free at the ends of the member. Because the cut strands tend to relax and attempt to return to their original untensioned state (but are unable to do so because of their bond with concrete), they compress the member.

If the strands are placed in the center of the member's cross section, a uniform compressive stress is produced over the entire cross section. Generally, however, the strands are placed eccentrically so that the prestress developed in the member is the reverse of the stresses that are expected to be produced by the loads.

For example, for a single-span beam supported at two ends, the strands are placed near the bottom of the beam, Figure 22.1(b), so that after the strands are released, compressive stresses are created at the bottom of the beam and an upward curvature (camber) is developed, Figure 22.1(c). When loads are applied, the beam deflects downward and becomes straight.

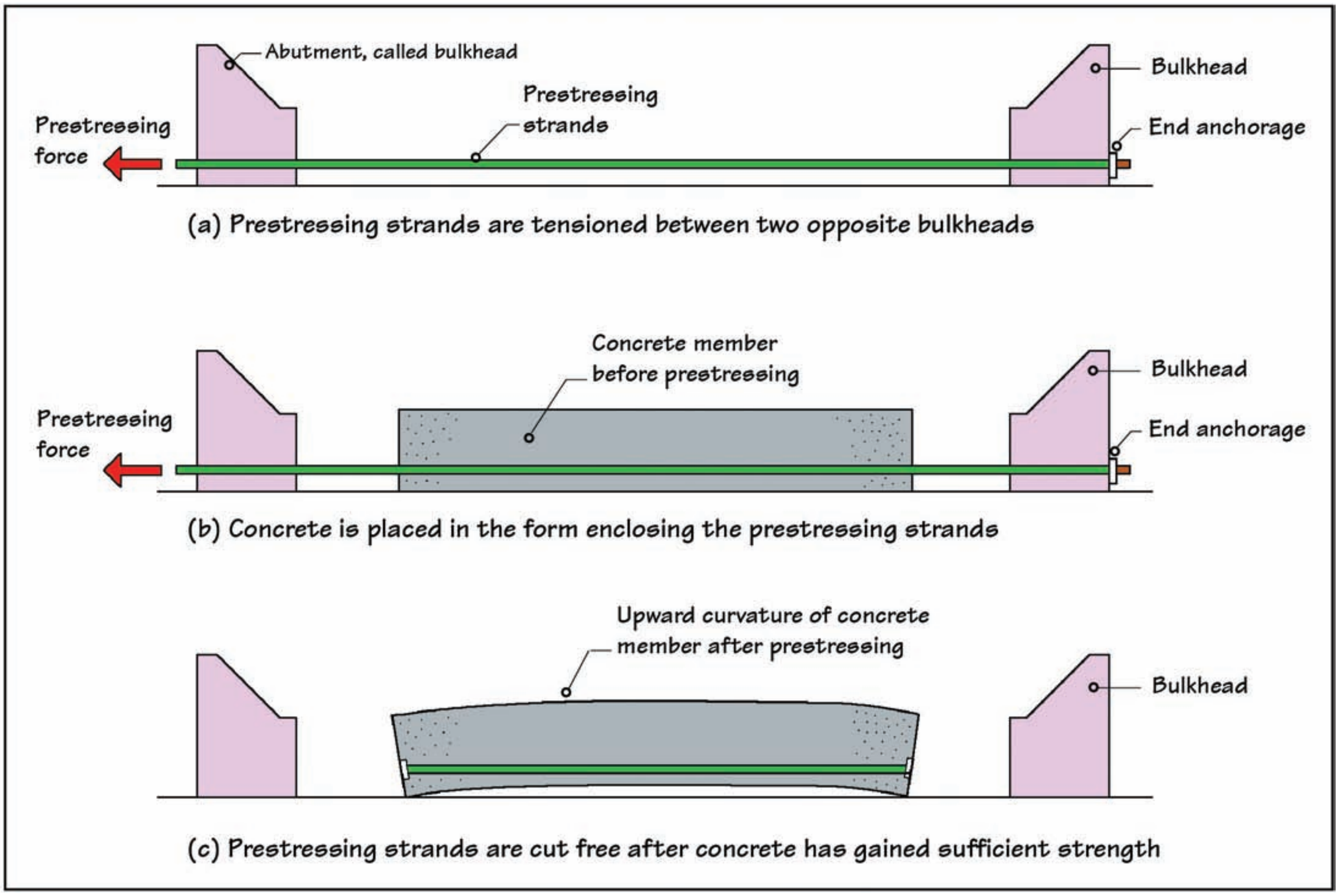

Abutment, called bulkhead
Prestressing strands
Bulkhead
Prestressing force
End anchorage
(a) Prestressing strands are tensioned between two opposite bulkheads
Concrete member before prestressing
Bulkhead
Prestressing force
End anchorage
(b) Concrete is placed in the form enclosing the prestressing strands
Upward curvature of concrete member after prestressing
Bulkhead
(c) Prestressing strands are cut free after concrete has gained sufficient strength

FIGURE 22.1 Three important stages in making a pretensioned (precast and prestressed) concrete member.

The strands shown in Figure 22.1 are straight. A more effective use of the strands is to profile them so that their eccentricity changes along the length of the member in response to the stresses created by the loads. In posttensioned concrete members, the profiling of strands (called *draped strands*) is in the shape of a smooth curve(see Figure 23.19). Due to the fabrication process, draped strands in pretensioned concrete members, however, must have abrupt changes in their profiles.

Posttensioning differs from pretensioning in that in posttensioning, the strands are tensioned after the concrete has been placed. The strands for posttensioning are encased in sleeves that are placed in the form before the concrete is placed. After the concrete has gained sufficient strength, the strands are tensioned. Because the strands are free to move within the sleeves, they can be tensioned without simultaneously tensioning the concrete. After tensioning of the strands to the extent required, they are anchored in that position by mechanical wedges at the member's ends, which restrains them from returning to their original (untensioned) state. The prestress created in the member by posttensioning is identical to that created by pretensioning.

STRANDS AND TENDONS

The combination of strands, sleeves, end anchorages, and so on, is referred to as *tendons*. The tendons are laid within the concrete forms in the same way as the reinforcing bars. A tendon may consist of one strand (see Figure 22.42) or multiple strands. (Because a strand is the most important component of a tendon, the strand is sometimes referred to as a tendon.)

ADVANTAGES AND DISADVANTAGES OF PRESTRESSING

There are several benefits of prestressing. The two most important ones are reduced cracking in concrete and the reduction in the dimensions of structural members, resulting in smaller dead loads and overall economy. The disadvantages of prestressing are the higher cost of tendons compared with reinforcing bars and the need for greater quality control and a more skilled labor force.

SITE-CAST CONCRETE AND PRECAST CONCRETE

Pretensioning is generally used for precast concrete members and is accomplished at the precaster's plant. Therefore, a pretensioned member is also called a *precast, prestressed member*. Precast, prestressed concrete members are transported to the construction site and assembled in a manner similar to that of structural steel members.

Posttensioning, on the other hand, is generally used for site-cast members and is done at the construction site. Thus, site-cast (also called *cast-in-place* or *CIP*) *concrete* may either be reinforced concrete or posttensioned concrete. (As illustrated in Chapter 23, reinforced-concrete structures can also be posttensioned, in which prestressing tendons and reinforcing bars are used in the same component.)

This and the following chapter are devoted to concrete construction. This chapter deals with various aspects of site-cast concrete construction, such as formwork and shoring, principles of reinforcing, and concrete surface finishes. Construction of concrete slabs-on-ground is also covered in this chapter. Other issues of concrete construction, such as site-cast and precast concrete framing systems, are discussed in Chapter 23.

EXPAND YOUR KNOWLEDGE

Some Important Terms

Reinforced Concrete and Nonprestressed Concrete

In concrete literature, the term *reinforced concrete* is also referred to as *nonprestressed concrete*. Similarly, steel reinforcement (steel rebars) is referred to as *nonprestressing reinforcement*. This recognizes that rebars and prestressing strands are two different types of concrete reinforcement. It also recognizes the growing use of prestressed concrete in buildings, so that referring to steel rebars as *conventional reinforcement* is becoming less common.

Site-Cast Concrete, Cast-in-Place Concrete, and Precast Concrete

Although the terms *site-cast concrete* and *cast-in-place concrete* are generally used interchangeably, there is a subtle difference between them. The terms *cast-in-place*, *cast-in-situation*, and *cast-in-situ* are synonymous; where the member is cast in the location where it is supposed to remain. This distinguishes it from a *site-precast* concrete member, which, although cast on site, is not cast in situ. For example, concrete tilt-up walls are site precast. Concrete tilt-up wall construction is covered in Chapter 26.

22.1 VERSATILITY OF REINFORCED CONCRETE

Reinforced concrete can be used for any structure, small, big, low-rise, or high-rise—in buildings, roads, bridges, tunnels, retaining walls, dams, and so on. In one form or another, reinforced concrete is used in almost every contemporary building, regardless of the geographical location.

The materials for reinforced concrete (crushed stone, sand, and water) are relatively inexpensive and locally available. In most locations, the steel required for reinforcing bars and the Portland cement are also locally produced. Additionally, the skill and training required for quality control in reinforced-concrete construction can be imparted to a local labor force far more easily than that required for steel construction (steel erection, welding, bolting, fire-retardant treatment, etc.).

The integral fire resistance of reinforced concrete and the various types of finishes that can be achieved add to its versatility, making it the most popular construction system. In many developing countries, reinforced concrete is used in almost every element of an architecturally significant building—structural frame, exterior and interior walls, basements, foundations, water-containing structures, pavements, street furniture, and so on, Figure 22.2.

The versatility of reinforced concrete is also due to the fact that the two structural materials (concrete and steel) are complementary, which allows variation in the size of a reinforced-concrete member for a given load and span. Thus, the size of a beam or column, providing the same strength, can be varied (to some extent) by varying the relative amounts of the two materials—a flexibility not available in steel or wood construction.

For instance, by increasing the amount of steel in a beam, it is possible to reduce the amount of concrete needed, or vice versa. The reduction in the amount of concrete results in a smaller beam size. (Note that the amount of steel even in a highly reinforced-concrete

NOTE

Concrete Construction and Building Codes

Because concrete is inherently fire enduring, concrete members can easily achieve the fire ratings required for Type I(A) construction—the most fire-resistive construction. For most occupancies, the building codes allow an unlimited area and an unlimited height if the building is built with Type I(A) construction. Unlike steel, concrete elements do not require add-on fire protection to meet the fire-rating requirements of a given type of construction.

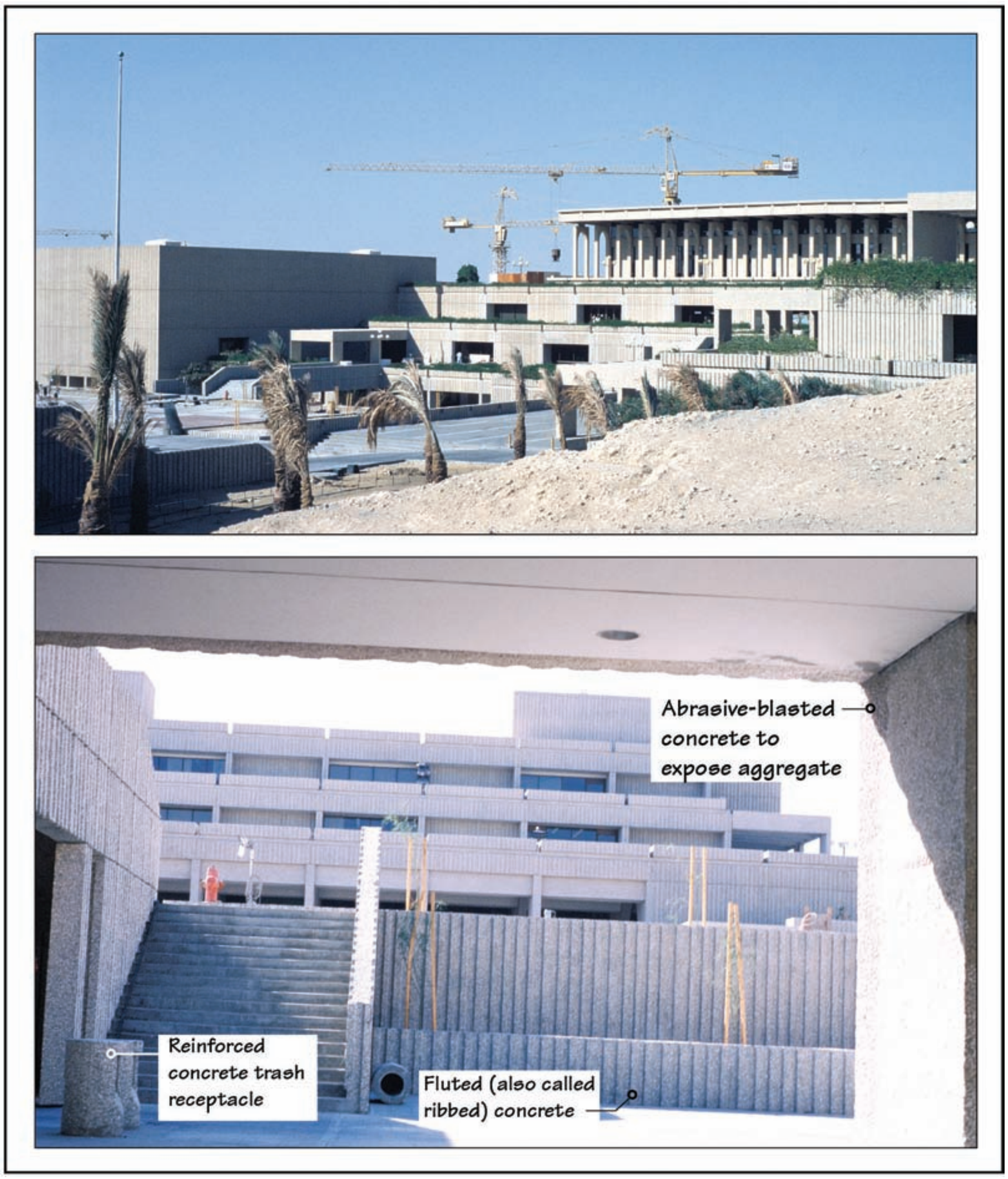

Abrasive-blasted concrete to expose aggregate
Reinforced concrete trash receptacle
Fluted (also called ribbed) concrete

FIGURE 22.2 Almost all buildings on the campus of King Fahd University of Petroleum and Minerals in Dhahran, Saudi Arabia are constructed of reinforced concrete. It has been used in the walls, structural frame, roof and floor slabs, stairs, water tower, roads and pavements, fountains, street furniture, etc., highlighting the versatility of this material.

beam seldom exceeds 2% of the beam's cross section. Therefore, a change in the amount of steel alters the beam's strength but does not impact the physical dimensions of the beam.)

22.2 CONCRETE FORMWORK AND SHORES

In reinforced-concrete construction, concrete and reinforcement must be contained in molds, referred to as *formwork*. The formwork for elevated slabs and beams must be supported on vertical supports, referred to as *shores*. Both formwork and shores are temporary structural elements that are removed after the reinforced-concrete members are able to support themselves.

For a reinforced-concrete slab-on-ground, the formwork is simple and generally consists of 2-by solid lumber (or plywood) edge forms braced by stakes, Figure 22.3. Shores are not required in this case because the concrete is ground supported.

For an elevated concrete slab, the formwork and shores are more complex. Figure 22.4 shows the formwork and shores for an elevated concrete slab without beams. The formwork for a complex floor system is more complicated. That is why the formwork in a typical reinforced-concrete building is generally the single most expensive item.

On average, the concrete costs nearly 25% to 30% of the cost of the structure (including placing and finishing of concrete), and steel reinforcement costs approximately 20% to

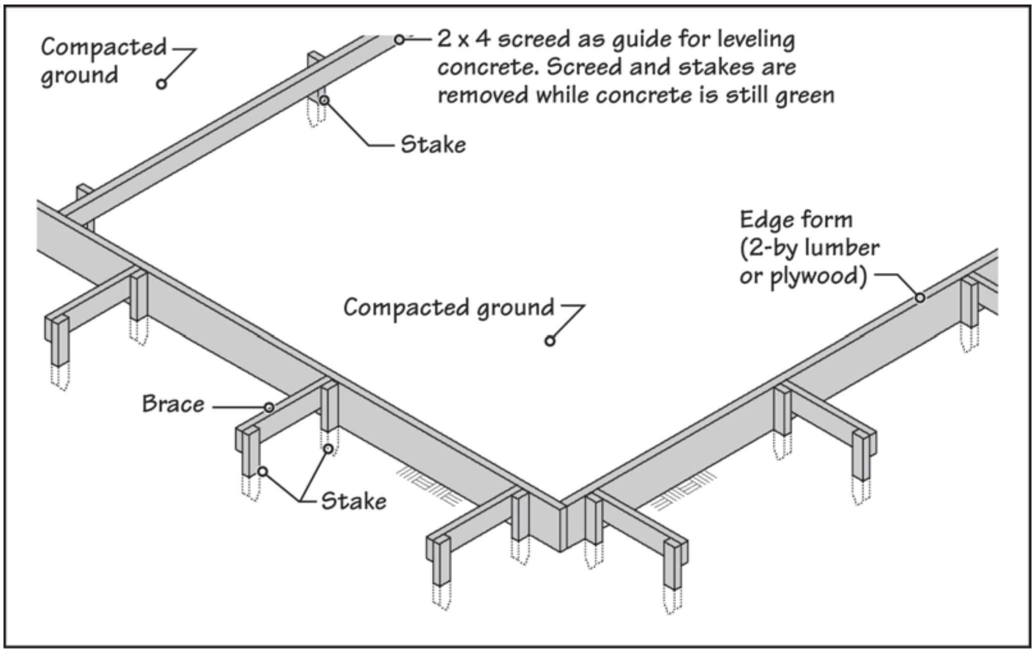

Compacted ground
2 x 4 screed as guide for leveling concrete. Screed and stakes are removed while concrete is still green
Stake
Edge form (2-by lumber or plywood)
Compacted ground
Brace
Stake

FIGURE 22.3 Formwork for a ground-supported concrete slab.

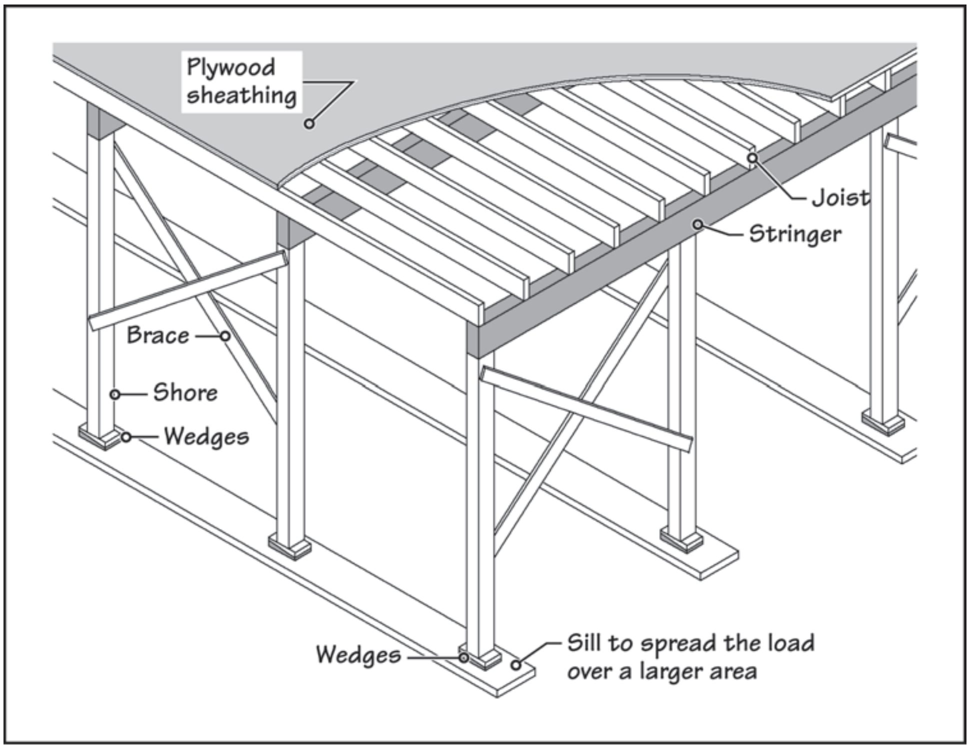

Plywood sheathing
Joist
Stringer
Brace
Shore
Wedges
Wedges
Sill to spread the load over a larger area

FIGURE 22.4 Formwork and shores for an elevated concrete slab. In this illustration, the shores and formwork are constructed of dimension lumber and plywood. As shown in Figure 22.11, steel and aluminum are also used as formwork and shoring materials.

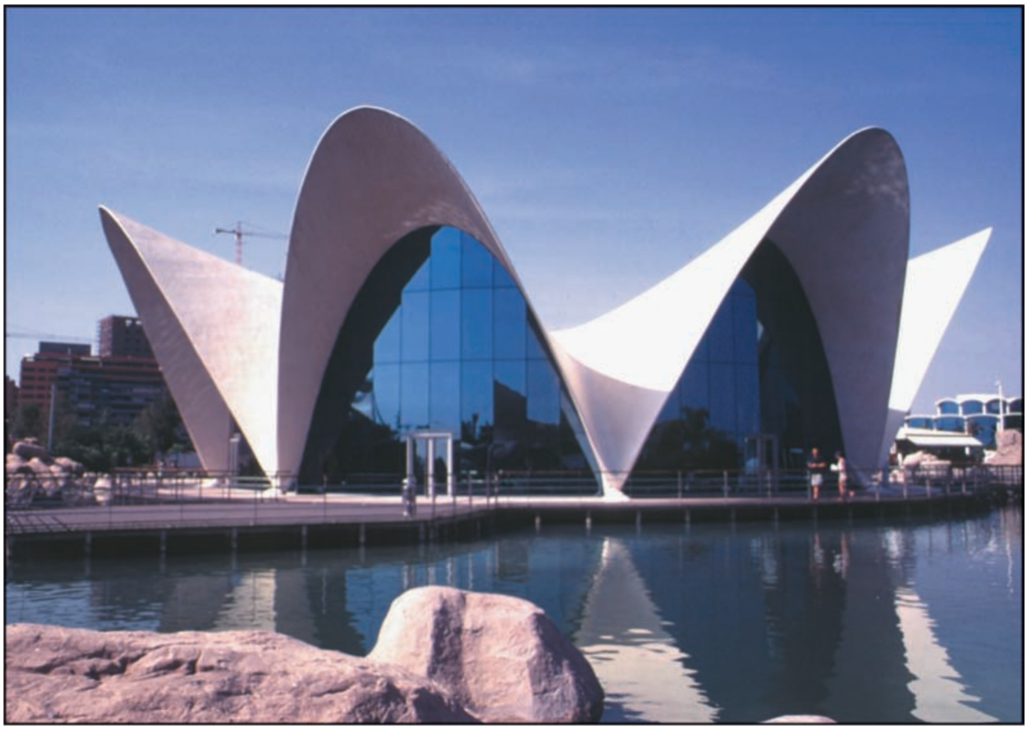


FIGURE 22.5 Reinforced-concrete shell roof in the Oceonographic Museum in the City of Arts and Sciences, Valencia, Spain, by architect Santiago Calatrava.

Observe the large roof span constructed of extremely thin concrete. The amount of reinforcement required is also small. Concrete shell structures are highly efficient in the use of materials because of their geometry, which induces mainly compression and very little bending stress in the structure. However, their geometry makes formwork extremely expensive. The overall cost of concrete shell roofs is quite high.

25% (including laying reinforcement in the forms, making reinforcement cages, etc.). The remaining 50% to 55% of the cost of the structure is in formwork.

For structures with complex geometries, the cost of formwork may exceed 75% of the total cost. The excessive cost of formwork is the primary reason why concrete shell roofs, Figure 22.5, are uncommon. This is despite the fact that the amount of concrete and steel required in these roofs is relatively small due to the inherent structural efficiency obtained from their geometry.

Formwork economy is, therefore, considered early in the design of a reinforced-concrete building. As far as possible, structural patterns and shapes that allow simple, standard, and reusable formwork are the best. Sizes of beams, columns, and other components should be repeated as much as possible.

For example, the size of columns should be kept the same from floor to floor by varying the strength of concrete and (or) the amount of reinforcement. Similarly, the width and depth of beams should be kept the same from bay to bay.

MATERIALS USED FOR FORMWORK AND SHORES

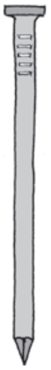
Criteria used in the selection of materials for formwork are cost, strength, reusability, durability, ease of assembly, and weight. The following materials generally satisfy these criteria.

Wood and Plywood Dimension lumber and plywood are the most commonly used form materials because of their cost, strength, nailability, and reusability. Lumber is commonly used in the supporting frame, and plywood is used as horizontal sheathing for floors and as vertical sheathing for beams, walls, and columns. Engineered lumber, such as laminated veneer lumber, is also used when its higher cost over dimension lumber is justified.

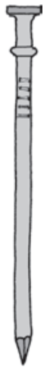
Form plywood is a special type of plywood that can withstand repeated wetting from concrete. It can also be obtained with an overlay lamination of smooth-surfaced materials, such as high-density overlay (HDO) and medium-density overlay (MDO). Laminations increase the durability of plywood and allow for easier stripping and cleaning of plywood for reuse.

In addition to several patented fasteners and clamps, common nails and duplex nails are used for fastening wood shores, braces, and forms. Wood shores may be supported on (hardwood) wedges that allow height adjustment and dismantling. Sill supports are required to spread the load on a larger area.

Several proprietary systems are available for adjusting the height of wood shores as alternatives to wedges. One system uses two overlapped shores clamped together with a patented device, Figure 22.6. Another system uses a screw-based steel assembly that is nailed to the bottom of a wood shore, Figure 22.7.



Common nail (see Figure 14.34, Chapter 14)



Duplex (doublehead) nail, used for temporary nailing

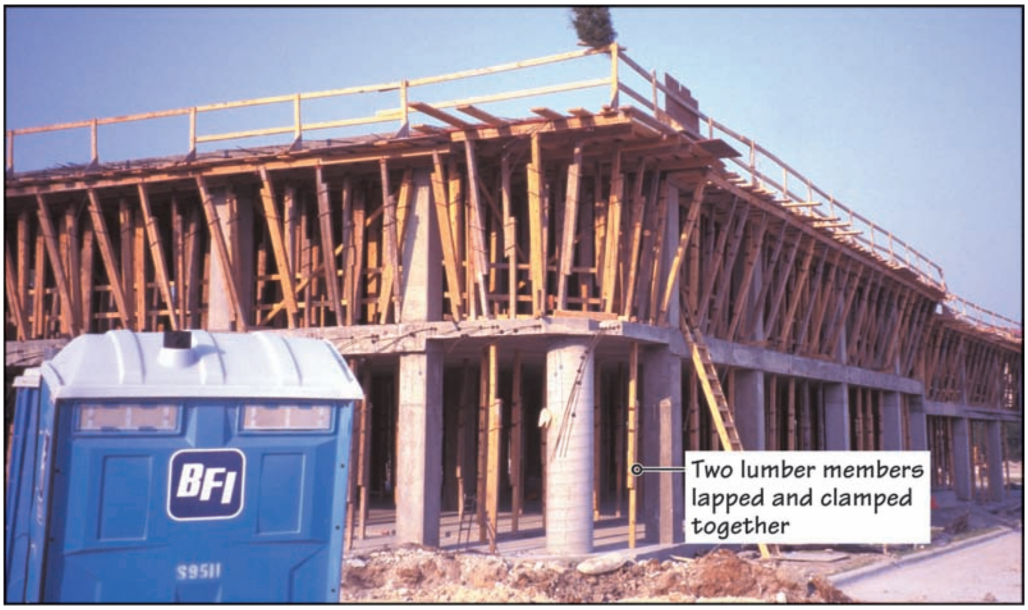

Two lumber members
lapped and clamped
together

FIGURE 22.6 Shores for a reinforced-concrete floor slab in which two-dimensional lumber members are lapped and clamped together with a patented device. The lapped and clamped assembly provides adjustment in the height of a shore.

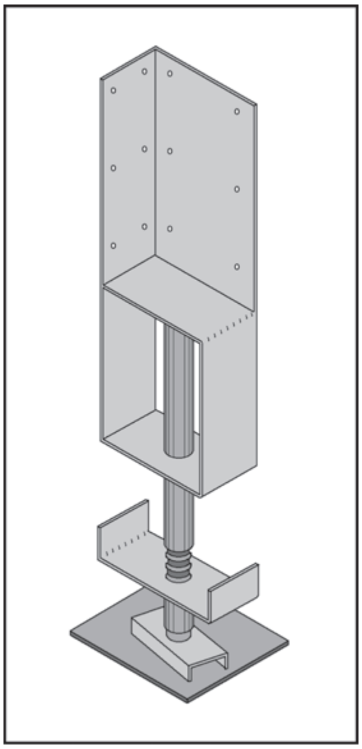


FIGURE 22.7 A screw-based metal assembly that can be nailed to one end of a lumber shore to give it height adjustability.

Steel Steel is also a commonly used form and shore material because of its high strength. Steel angles, channels, and prefabricated steel joists are used in the supporting frame for slab forms and shores. The use of steel joists can substantially reduce the congestion of shores that typically occurs with lumber-based formwork.

Steel pipe shores can be used as individual shores, but they are more commonly used as scaffold-type framed shores. They are generally provided with screw-type adjustment at the bottom and an adjustable head at the top, Figure 22.8.

Aluminum as Form Material Aluminum alloys (which do not react with fresh concrete) are being increasingly used as form material because of their lighter weight and

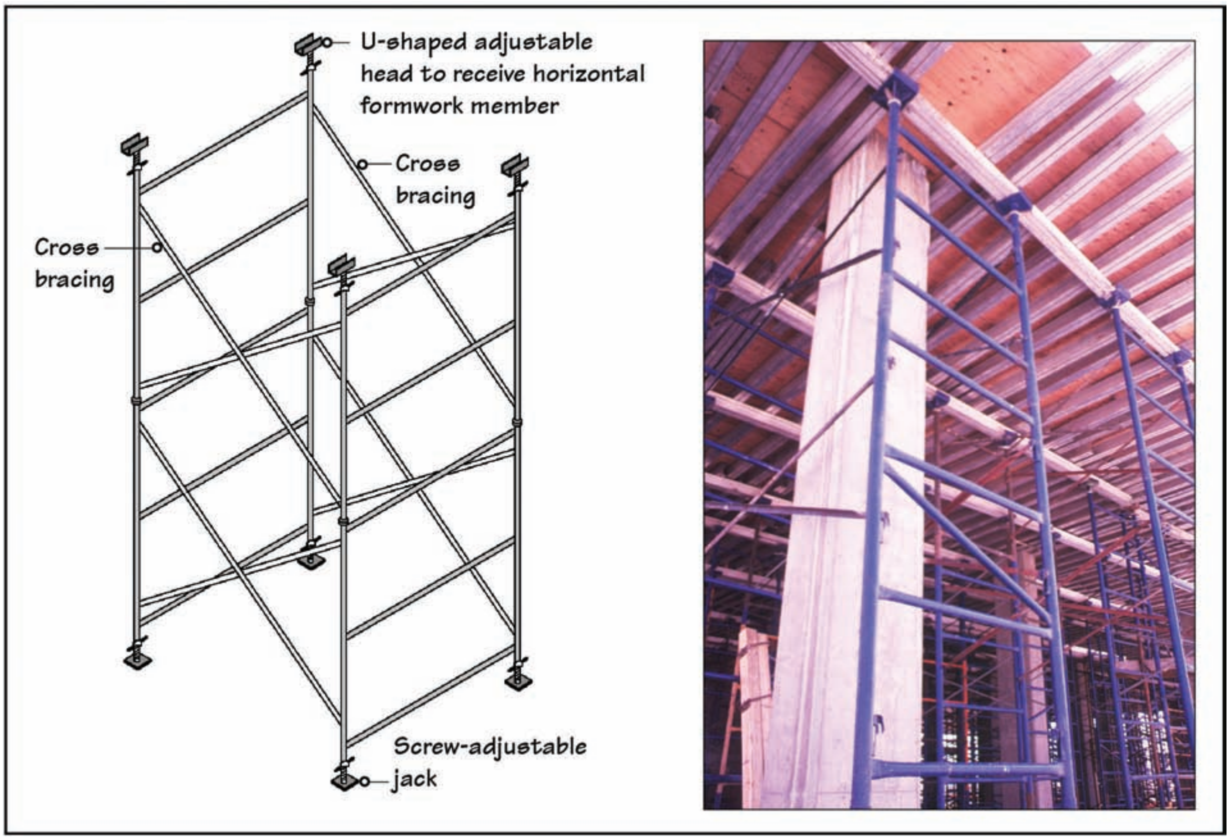

U-shaped adjustable
head to receive horizontal
formwork member
Cross
bracing
Cross
bracing
Screw-adjustable
jack

FIGURE 22.8 Steel pipe scaffold shores are available in panel frames in widths of 2 ft to 5 ft and heights of 4 ft to 6 ft. Panel frames can be assembled vertically and braced diagonally to make a stable shore frame.

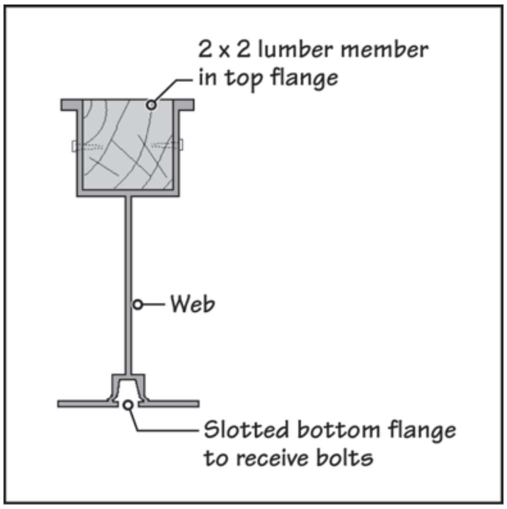

2 x 2 lumber member in top flange
Web
Slotted bottom flange to receive bolts

FIGURE 22.9 A typical extruded aluminum section used as a joist for formwork.

high strength-to-weight ratio. Generally, aluminum angles are used in trusses or in extruded one-piece joists with U-shaped flanges to provide nailing and bolting capabilities, Figure 22.9.

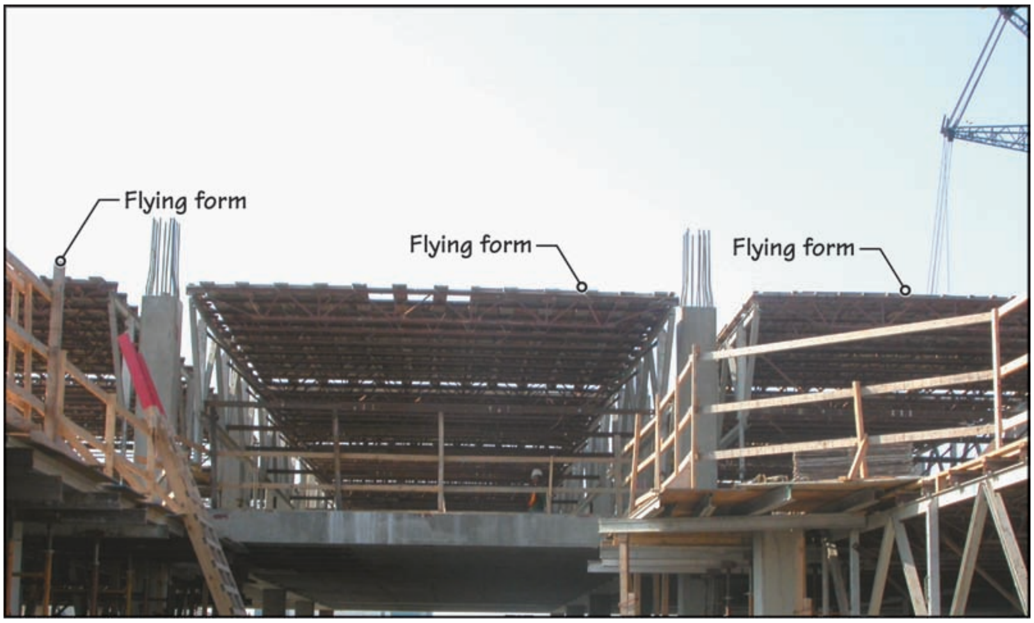
Glass Fiber–Reinforced Plastic (GFRP) as Form Material Because it can be molded into shape and has a smooth surface, GFRP is commonly used for pans and domes required for one-way or two-way joist floor systems (see Chapter 23).

PREFABRICATED PANEL FORMS

Because the major cost of formwork in a multistory building is in the floors, it is fairly common to prefabricate the formwork and shores for each bay of the floor as a complete unit and "fly" it into position with a crane, Figure 22.10. The form units, referred to as *flying forms*, are generally complete, freestanding units with their own adjustable shores designed for easy removal and hoisting to the next level, Figure 22.11.

The term *flying form* is typically used with floor slab forms, but other large prefabricated panel forms (called *gang forms*) are also used for walls and other reinforced-concrete elements.

FIGURE 22.10 Formwork for an entire bay between columns can be assembled as a large panel and "flown" into position by a crane. Referred to as *flying forms*, these panels can be demounted with the help of jacked shores and lifted to the next floor for reuse. Flying forms are particularly convenient in mid- and high-rise buildings with identical dimensions of floor slab components. In this figure, the right-hand panel is being lowered into position by the crane.


Flying form
Flying form
Flying form

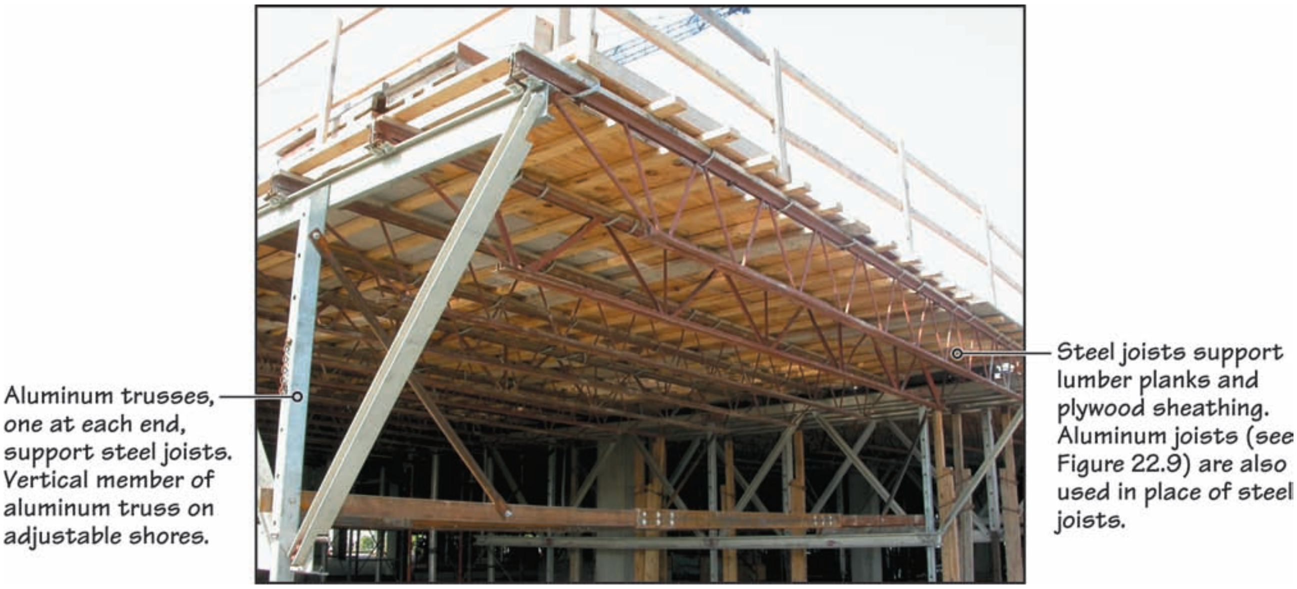

Aluminum trusses, one at each end, support steel joists. Vertical member of aluminum truss on adjustable shores.
Steel joists support lumber planks and plywood sheathing. Aluminum joists (see Figure 22.9) are also used in place of steel joists.

FIGURE 22.11 Details of the panelized flying form in Figure 22.10. The panel consists of steel joists that are supported on two aluminum trusses, one at each end. The vertical members of trusses extend down to form shores, which are provided with adjustable jacks. The steel joists support lumber planks, which in turn support plywood sheathing.

Each question has only one correct answer. Select the choice that best answers the question.

1. According to building codes, plain concrete (concrete without steel reinforcement) is not permitted in new construction.
- **a.** True
- **b.** False

2. The yield strength of prestressing steel is
- **a.** 40 ksi.
- **b.** 50 ksi.
- **c.** 60 ksi.
- **d.** 100 ksi.
- **e.** none of the above.

3. The term *prestressed concrete* refers to both pretensioned and posttensioned concrete.
- **a.** True
- **b.** False

4. Which of the following statements is true?
- **a.** The term *strands* includes tendons.
- **b.** The term *tendons* includes strands.
- **c.** The term *tendons* refers to reinforcing bars that have been bent to required shapes.
- **d.** The term *strands* refers to reinforcing bars that have been bent to required shapes.
- **e.** None of the above.

5. Which of the following statements is true?
- **a.** Pretensioning is generally done at the construction site and yields a precast, prestressed concrete member.
- **b.** Pretensioning is generally done at the precaster's plant and yields a precast, prestressed concrete member.
- **c.** Posttensioning is generally done at the construction site and yields a precast, posttensioned concrete member.
- **d.** Posttensioning is generally done at the precaster's plant and yields a precast, posttensioned concrete member.

6. In a typical site-cast reinforced-concrete structure, the cost of formwork and shores is
- **a.** approximately equal to the combined cost of concrete and steel.
- **b.** approximately 75% of the combined cost of concrete and steel.
- **c.** approximately 50% of the combined cost of concrete and steel.
- **d.** approximately 25% of the combined cost of concrete and steel.
- **e.** none of the above.

7. Concrete shell roofs are not commonly used because
- **a.** they require a relatively large amount of concrete per square foot of floor area.
- **b.** they require a relatively large amount of steel reinforcement per square foot.
- **c.** they require prestressing, which substantially raises their cost.
- **d.** all of the above.
- **e.** none of the above.

8. In site-cast concrete construction, shores are used
- **a.** in ground-supported concrete slabs.
- **b.** in elevated concrete slabs.
- **c.** as formwork for concrete walls.
- **d.** as formwork for concrete columns.
- **e.** none of the above.

9. Height adjustability in shores made of dimension lumber
- **a.** is provided through lapped members clamped together with specially made clamps.
- **b.** is provided through a screw-based metal assembly.
- **c.** is provided through (a) or (b).
- **d.** is not provided.

10. Scaffold-type shores are generally made from
- **a.** dimension lumber.
- **b.** plywood.
- **c.** steel pipes.
- **d.** steel plates.
- **e.** all of the above.

11. High-density overlay (HDO) on form plywood
- **a.** improves the strippability of forms.
- **b.** allows easier cleaning of forms.
- **c.** increases reusability of forms.
- **d.** all of the above.
- **e.** none of the above.

12. Aluminum is commonly used as form and shore material because
- **a.** it is chemically compatible with wet concrete.
- **b.** it is an easily nailable material.
- **c.** its strength-to-weight ratio is low, which reduces the weight of forms and shores.
- **d.** its strength-to-weight ratio is high, which reduces the weight of forms and shores.
- **e.** all of the above.

13. The term *flying form* refers to
- **a.** a large formwork assembly for floor slabs.
- **b.** a large formwork assembly for roof slabs.
- **c.** a large formwork assembly for floor and roof slabs.
- **d.** a large formwork assembly for concrete walls.
- **e.** a large formwork assembly for columns.

22.3 FORMWORK REMOVAL AND RESHORING

To speed construction, forms and shores are removed as soon as possible. Another advantage of early removal of formwork is that if repair or patching of a concrete surface is needed, it can be accomplished while the concrete is in the early stages of curing, favorable to a good bond.

However, premature removal of forms may not only be dangerous but also affect the quality of the finish. The time between the end of concreting and the removal of forms (referred to as the *stripping time*) is a function of the ambient temperature, strength of concrete, and the type of component. Higher ambient temperature and higher strength of concrete require less stripping time. Forms from vertical surfaces of members, such as column forms, the sides of beams, and slabs, can be removed earlier. After their removal, concrete surfaces are generally wrapped with blankets or burlap and moist cured.

Forms from the horizontal surfaces can be removed only when the concrete has gained sufficient strength to support itself, which is generally assumed to be 70% of the specified strength of concrete. Stripping time is typically specified by the project's structural engineer.

RESHORING

After the formwork from the horizontal surfaces of the structure (beams and slabs) is stripped and moved to the next higher level, the surfaces are supported by shores, a process

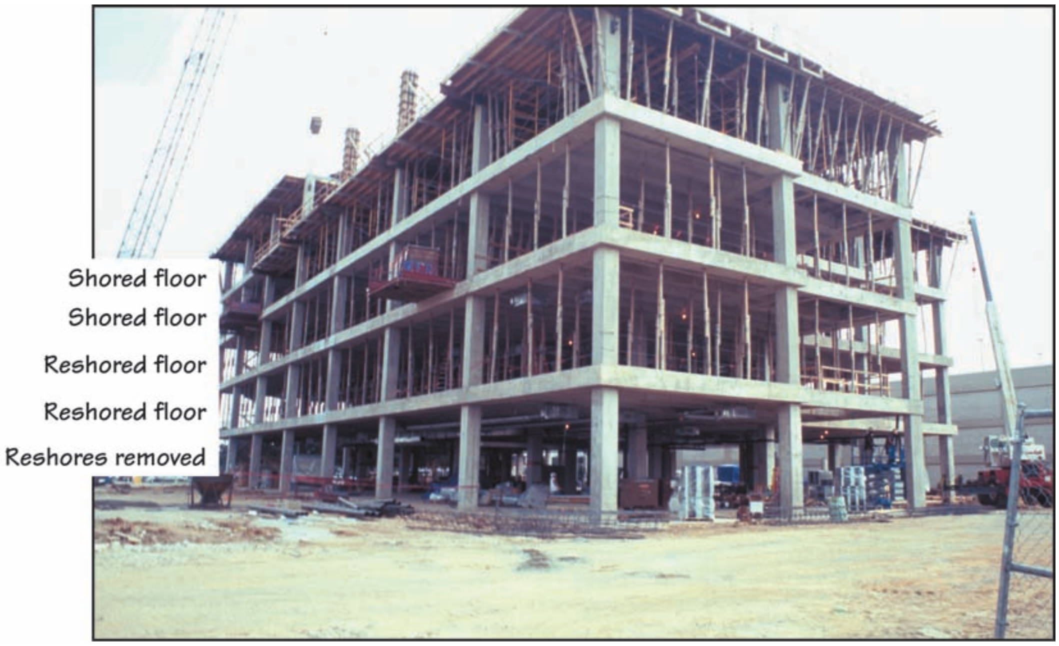


FIGURE 22.12 In this building under construction, the concreting for the top floor has been completed and the forms for the next floor are being installed. The two underlying floors have been reshored, while the reshores from the ground floor have been removed to allow interior construction. As far as possible, reshores must align in the same vertical position from floor to floor.

called *reshoring*. Reshoring facilitates maximum reuse of formwork by taking advantage of the partial strength of the lower floors to support the weight of wet concrete on the floors above. Other objectives of reshoring are as follows:

- To prevent deflection and creep of concrete (concrete that has not gained sufficient strength creeps and deflects more)
- To reduce hairline cracks in concrete

In a multistory building, where floors are generally cast 7 to 10 days apart, one shored story and two reshored stories are generally required below the story on which wet concrete is placed. This requirement is relaxed if there is a longer gap between the construction of the floors, Figure 22.12. Reshores are generally placed in the same vertical position from floor to floor.

FORM RELEASE AGENTS

Before concrete is placed in the forms, their interior surfaces are coated with release agents to allow the forms to be stripped without damage to both the forms and the concrete. Release agents lubricate the surfaces and, in the case of wood and plywood forms, they also seal the surfaces against water absorption, which increases form life. Various proprietary release agents are available, which are either oil- or wax-based coatings. Better-quality release agents allow several reuses of forms between coatings.

RESPONSIBILITY FOR FORMWORK DESIGN

The structural safety of formwork and shores is obviously vital. Because construction site safety is in the realm of the general contractor (see Chapter 1), the structural design of formwork is also the general contractor's responsibility. Thus, the general contractor is free to choose the forming and shoring systems that will yield an economical structure within the requirement of the finished product specified by the architect/engineer.

22.4 ARCHITECTURAL CONCRETE AND FORM LINERS

In the early days of its development, concrete was considered only an engineering material, suitable for gutters, sewers, pavements, roads, and structural frames of buildings. It was considered unsuitable for building facades because of its dull gray, unappealing appearance, which deteriorates with time because of shrinkage cracks, attracting dust and moss.

Le Corbusier was among the pioneers who, apart from exploiting its sculptural properties, made concrete count as an architectural material—suitable for building facades and interiors. In most of Le Corbusier's buildings, *smooth, off-the-form concrete* was used; that is, concrete was left exposed (in its natural state), without any additional surface treatment.

An acceptable surface quality straight from the forms can be obtained only if the formwork surface is good, the concrete has an optimum water-cement ratio, and the concrete is vibrated sufficiently to avoid honeycombing. Excessive vibration can cause bleeding or separate the ingredients.

SMOOTH, OFF-THE-FORM CONCRETE

Although smooth, off-the-form concrete provides the most economical surface finish, it is generally not recommended for contemporary facades or interiors because of the following reasons:

- Color variations are difficult to avoid between batches of concrete, particularly with gray Portland cement. They are relatively easier to control with (more expensive) white Portland cement and are less noticeable with aesthetic (relief) joints on the surface.
- Smooth forms should be free from surface imperfections. Additionally, with smooth forms, the vibration of forms is recommended unless care is taken to ensure that internal vibrators do not damage form surfaces.
- Repair of smooth-surface concrete after removal of the formwork is generally noticeable.

TEXTURED CONCRETE SURFACES

Because of the concerns with smooth, off-the-form concrete, the use of textured concrete is more common for building facades. (Interior application of textured concrete is relatively uncommon because of its propensity to collect dust.) Textured concrete surfaces can be obtained by: (a) surface treatment after formwork removal, (b) using form liners, or (c) both.

The following are commonly used surface treatments on concrete after removal of the forms:

- **Exposed aggregate finish by water washing:** This is achieved by applying chemical retarders on formwork, which retards the setting of concrete near the surface. After removal of the form, the surface layer of concrete (cement-and-fine-aggregate paste) is carefully removed by pressure washing with water to expose the coarse aggregates. Retarders that expose coarse aggregates to various depths (generally up to one-third of its size) are available.
- **Abrasive blasting:** Depending on the type of abrasive and the amount of pressure applied, abrasive blasting can be light, medium, or heavy. The difference between the three types is easily noticeable (see Figure 28.34). Blasting removes the natural gloss of aggregates and provides a mat (nonglossy) appearance compared with that obtained from chemical retarders.
- **Acid etching:** Acid etching involves removing surface cement paste with dilute hydrochloric acid, which reveals the sand and a small percentage of coarse aggregate. In this application, acid-resistant sand and coarse aggregate are recommended (such as quartz or granite). Carbonate aggregates, such as marble, limestone, and dolomite, are not acid resistant (see Chapter 25).

ARCHITECTURAL CONCRETE THROUGH FORM LINERS

A large variety of textures and patterns can be created on concrete by lining the formwork with the required pattern. The use of form liners is generally more economical than modifying the concrete surface after removing the forms. One of the several commonly used patterns obtained by using form liners is shown in Figure 22.13. Form liners, which are generally made from polymeric materials, are available for single or repeat applications (see Figure 28.43).

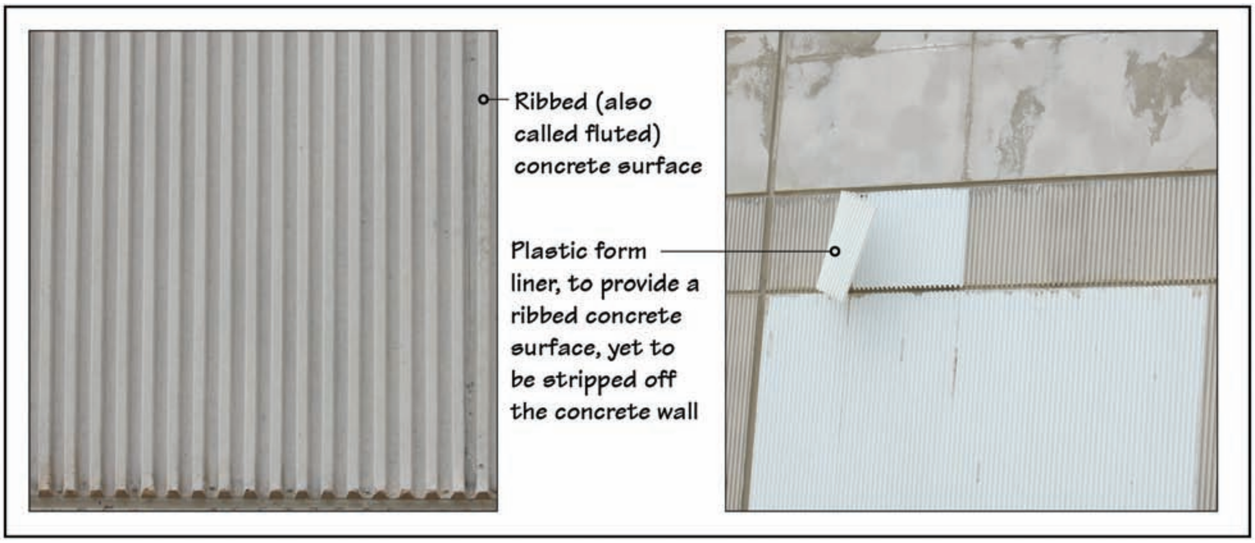

Ribbed (also called fluted) concrete surface
Plastic form liner, to provide a ribbed concrete surface, yet to be stripped off the concrete wall

FIGURE 22.13 Ribbed concrete surface produced using a ribbed form liner. Several other surface textures can be obtained in architectural concrete through the use of form liners.

They are attached to the formwork or casting beds (for tilt-up concrete walls or precast concrete panels).

22.5 PRINCIPLES OF REINFORCING CONCRETE

A reinforced-concrete member must obviously have an adequate amount of steel. In addition, the reinforcement must be placed in the correct location. Sometimes a seemingly trivial error in the location of reinforcement can have serious consequences. For example, because an overhanging portion of a concrete slab is subjected to tension at its top surface (and compression at the bottom), the reinforcement must be located near the top surface. If the reinforcement is inadvertently located at the bottom of the slab (as is generally the case with slabs without overhangs), the slab may collapse when the formwork is removed. Such mistakes, though not common, have occurred in buildings with poor inspection protocols.

In addition to the amount and location, there are several other issues related to reinforcement. Consider a typical reinforcement cage for a simply supported beam, Figure 22.14.

NOTE

Simply Supported Beams and Continuous Beams

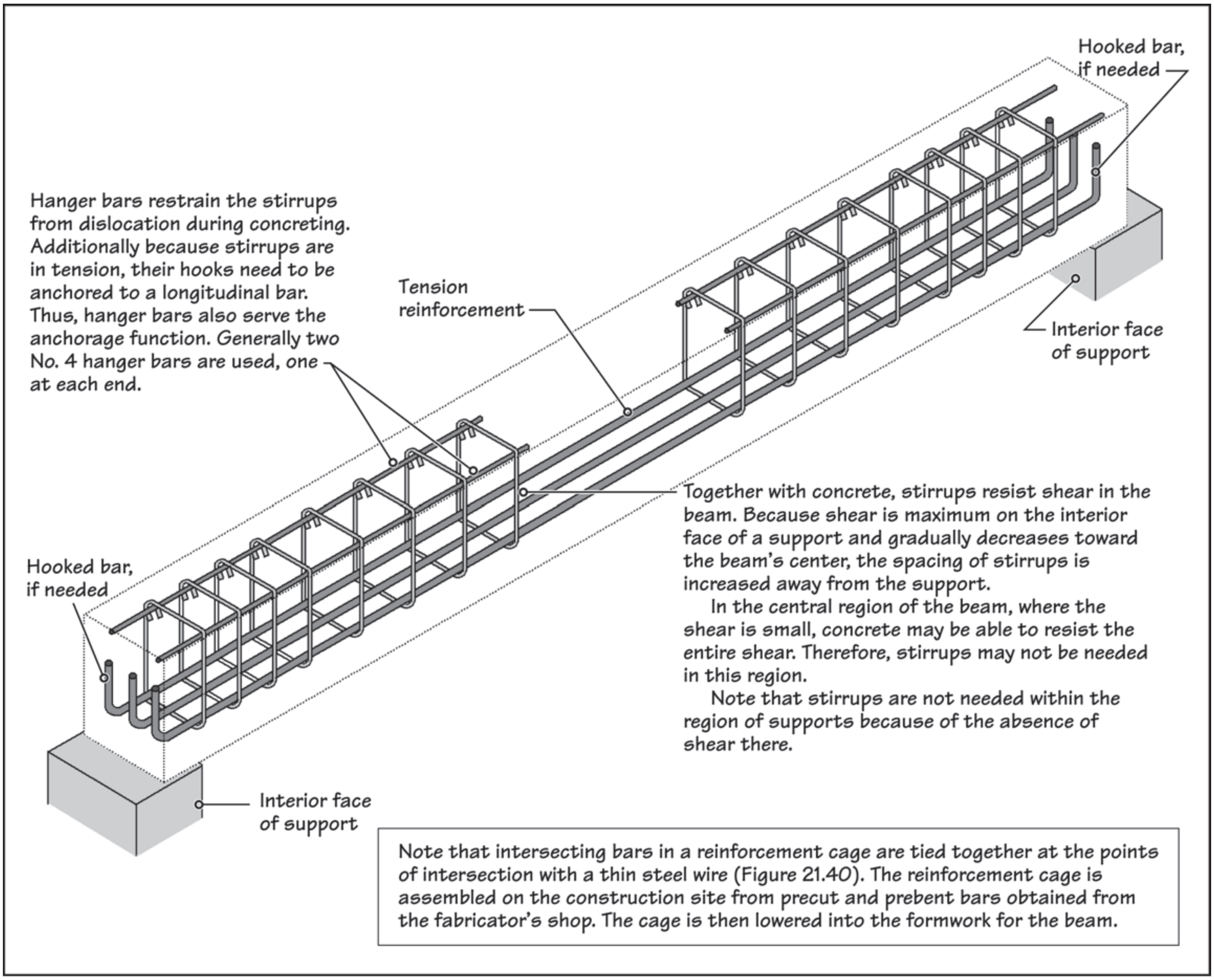
A simply supported beam is a beam that bears on two end supports. When the beam bends under loads, the ends of the beam rotate freely; that is, the supports do not present any restraint to end rotation.

A beam whose ends are framed into a column is unable to rotate freely at the ends, such as the continuous beam of Figure 22.18.

TENSION REINFORCEMENT, STIRRUPS, AND HANGER BARS

Under gravity loads, a *simply supported beam* is subjected to tensile stresses at the bottom and compressive stresses at the top. Reinforcement is, therefore, required at the beam's bottom, referred to as *tension reinforcement*. No bars are required at the top of the beam unless it also has compression reinforcement.

In addition to tension reinforcement, stirrups are generally required in a beam to resist shear. Also referred to as *shear reinforcement*, stirrups are typically made from No. 3 or No. 4 bars. In response to the decreasing shear force in a beam away from the supports, stirrup



Hanger bars restrain the stirrups from dislocation during concreting. Additionally because stirrups are in tension, their hooks need to be anchored to a longitudinal bar. Thus, hanger bars also serve the anchorage function. Generally two No. 4 hanger bars are used, one at each end.

Together with concrete, stirrups resist shear in the beam. Because shear is maximum on the interior face of a support and gradually decreases toward the beam's center, the spacing of stirrups is increased away from the support.

In the central region of the beam, where the shear is small, concrete may be able to resist the entire shear. Therefore, stirrups may not be needed in this region.

Note that stirrups are not needed within the region of supports because of the absence of shear there.

Note that intersecting bars in a reinforcement cage are tied together at the points of intersection with a thin steel wire (Figure 21.40). The reinforcement cage is assembled on the construction site from precut and prebent bars obtained from the fabricator's shop. The cage is then lowered into the formwork for the beam.

FIGURE 22.14 Reinforcement cage for a simply supported, reinforced-concrete beam.

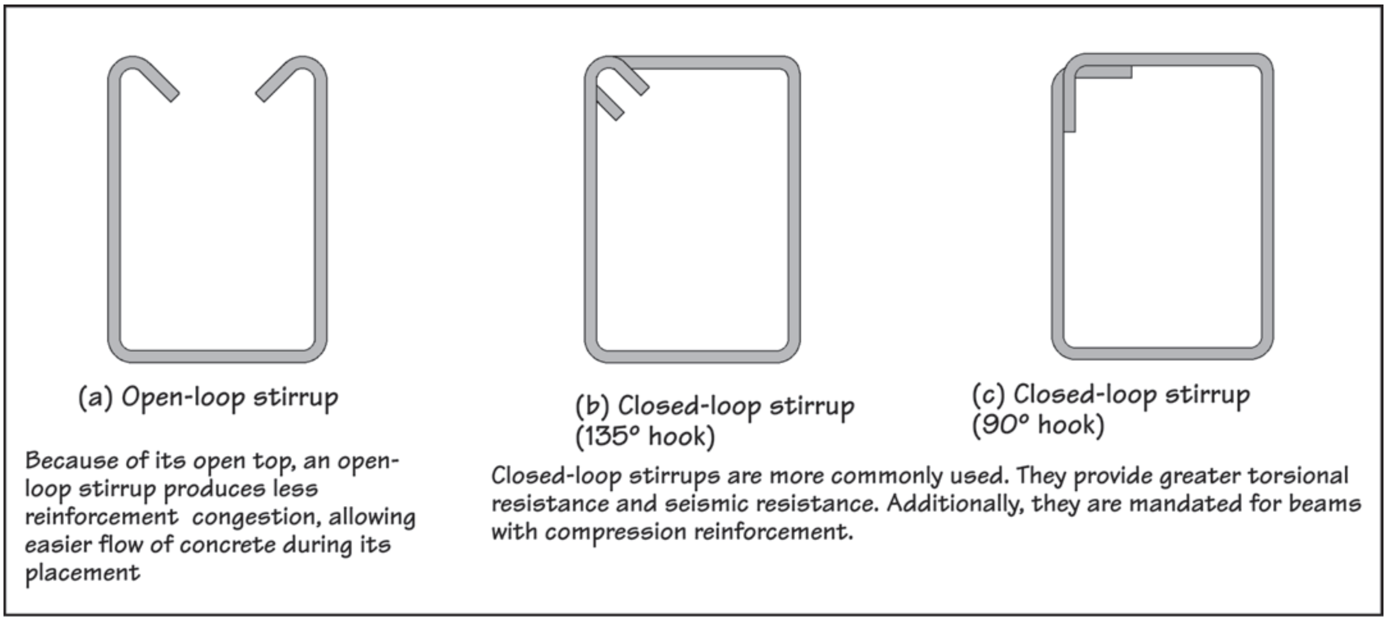

(a) Open-loop stirrup
Because of its open top, an open-loop stirrup produces less reinforcement congestion, allowing easier flow of concrete during its placement
(b) Closed-loop stirrup (135° hook)
(c) Closed-loop stirrup (90° hook)
Closed-loop stirrups are more commonly used. They provide greater torsional resistance and seismic resistance. Additionally, they are mandated for beams with compression reinforcement.

FIGURE 22.15 Commonly used stirrup shapes.

spacing is increased from the face of the support toward the beam's center. No change is made in the diameter of stirrup bars.

Stirrups generally consist of a loop with two vertical legs. Because only the vertical legs of a stirrup resist shear, stirrups can be open-loop stirrups, Figure 22.15(a). Open-loop stirrups reduce reinforcement congestion and allow easier placement of concrete. Closed-loop stirrups are more commonly used, Figures 22.15(b) and 22.15(c), and are mandated in seismic zones, where stress reversal may occur, and in beams with compression reinforcement.

BEAMS WITH COMPRESSION REINFORCEMENT (DOUBLY REINFORCED BEAMS)

A reduction in the size of a reinforced-concrete beam for a given span and load can be obtained by increasing the amount of tension reinforcement. If the tension reinforcement cannot be accommodated in a single layer (Figure 22.14), it may be provided in two layers, Figure 22.16.

However, the American Concrete Institute (ACI) Code does not allow an increase in tension reinforcement beyond a certain percentage. This is to ensure a ductile failure of the beam under an overload. For further reduction in beam size, additional steel may be used in the compression region, that is, at the top of a simply supported beam, referred to as *compression reinforcement*. When compression reinforcement is used in a simply supported beam, it runs continuously from support to support, like the tension reinforcement. Hanger bars are not required in this beam type, and stirrups are required throughout the beam's length.

A beam provided with compression reinforcement is called a *doubly reinforced beam*, Figure 22.17. A beam with tension reinforcement only, such as that shown in Figure 22.16, is called a *singly reinforced beam*.

CONTINUITY IN REINFORCED-CONCRETE MEMBERS

A single-span, simply supported beam (Figure 22.14) is seldom used in site-cast reinforced-concrete construction. Instead, reinforced-concrete members are generally continuous, which creates a stress pattern different from that of a simply supported beam. For instance, in the three-span beam-column frame of Figure 22.18(a), tension is created at the bottom of the beam in the middle region and at the top of the beam near the supports. The reinforcement in such a beam is, therefore, more complex, Figure 22.18(b). Note that both top and bottom longitudinal bars in the beam are tension-reinforcing bars.

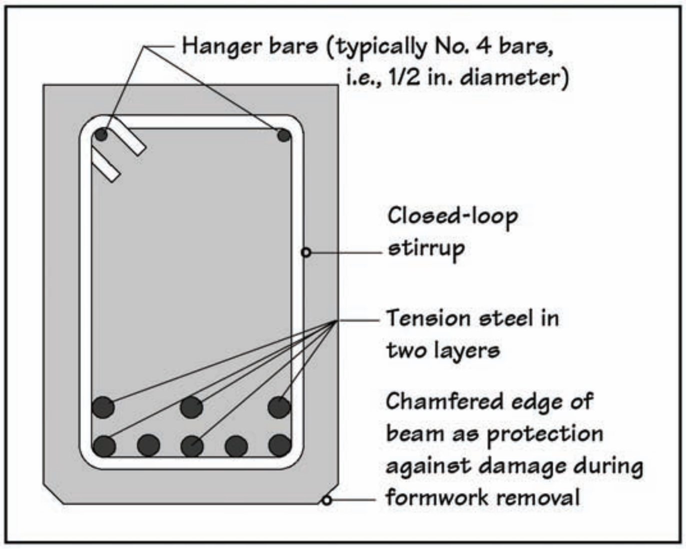

Hanger bars (typically No. 4 bars, i.e., 1/2 in. diameter)
Closed-loop stirrup
Tension steel in two layers
Chamfered edge of beam as protection against damage during formwork removal

FIGURE 22.16 A concrete beam with tension steel in two layers. Note that the function of hanger bars is only to tie the stirrups at the top; they have no structural function.

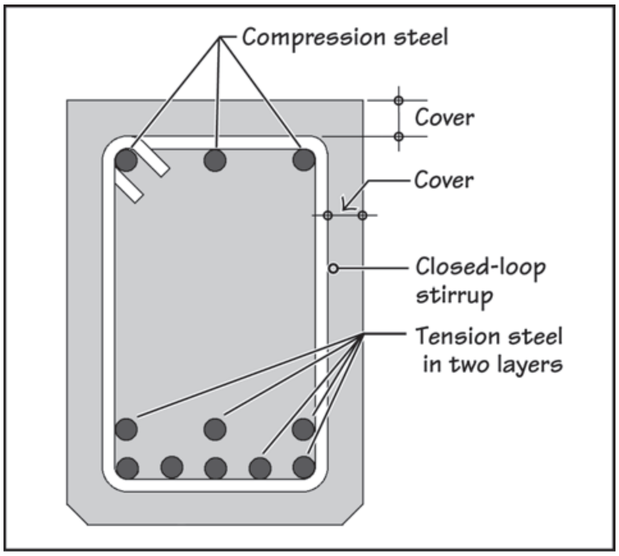
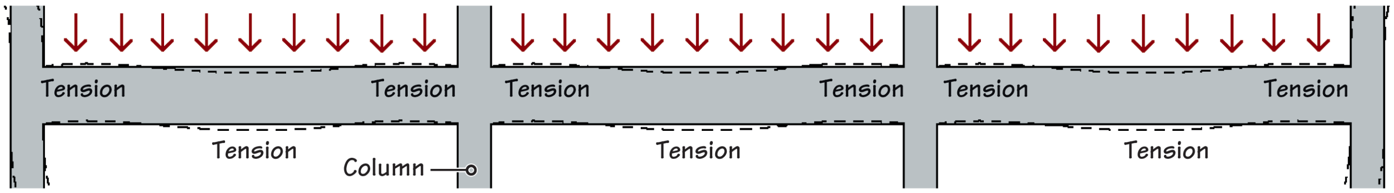
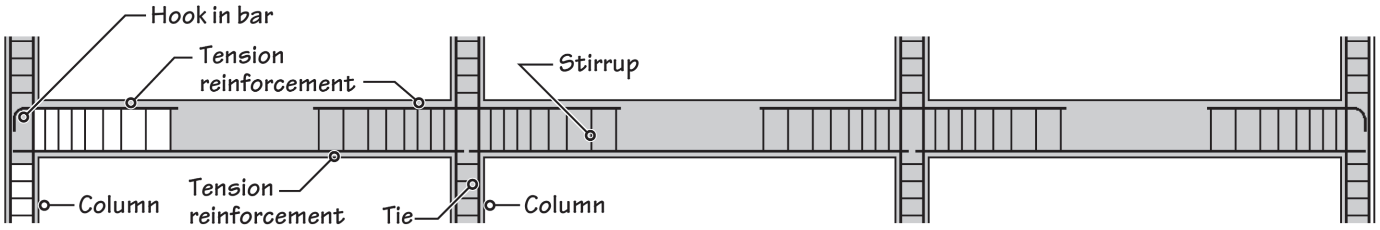

Compression steel
Cover
Cover
Closed-loop stirrup
Tension steel in two layers

FIGURE 22.17 A section through a doubly reinforced-concrete beam. The beam shown in Figure 22.16 (and also in Figure 22.14) is a singly reinforced beam.



(a) A continuous column-beam frame and its deflected shape (shown by dashed lines) under the loads



(b) Reinforcement details for the column-beam frame shown in (a)

FIGURE 22.18 Reinforcement details in a column-beam frame in response to the stresses created by the loads. Note that the longitudinal bars at both the top and bottom of the beam are tension-reinforcing bars.

22.6 SPLICES, COUPLERS, AND HOOKS IN BARS

Reinforced concrete can function as a structural material only if there is a perfect bond (adhesion) between the concrete and the reinforcing bars. This bond allows two lengths of reinforcing bars to function as one continuous bar through lap splices. Because reinforcing bars are available in finite lengths (generally up to a maximum of 60 ft), lap splicing allows reinforcement to extend continuously in long beams, large slabs, and multistory columns.

Because concrete works as glue, the stress in a bar is transferred to concrete and from there to the lapped adjacent bar, Figure 22.19(a). This is similar to joining two strips of cardboard by lapping them and placing glue in the lap to make them function as one continuous strip. The greater the force to be transferred from one strip to the other, the greater the required lap length and/or the need for stronger glue, Figure 22.19(b).

Because reinforcement is designed to be under maximum stress (60 ksi for Grade 60 steel), lap splice lengths have been standardized for bars of different diameters, concrete strength, and steel grade. Splices are generally located in places of minimum stress in the member. In columns, however, they generally are located at the floor level for convenience, Figure 22.20. One way to splice column reinforcement is to bend the top of the lower column bars inward to accommodate the lapped bars from the upper column, Figure 22.21.

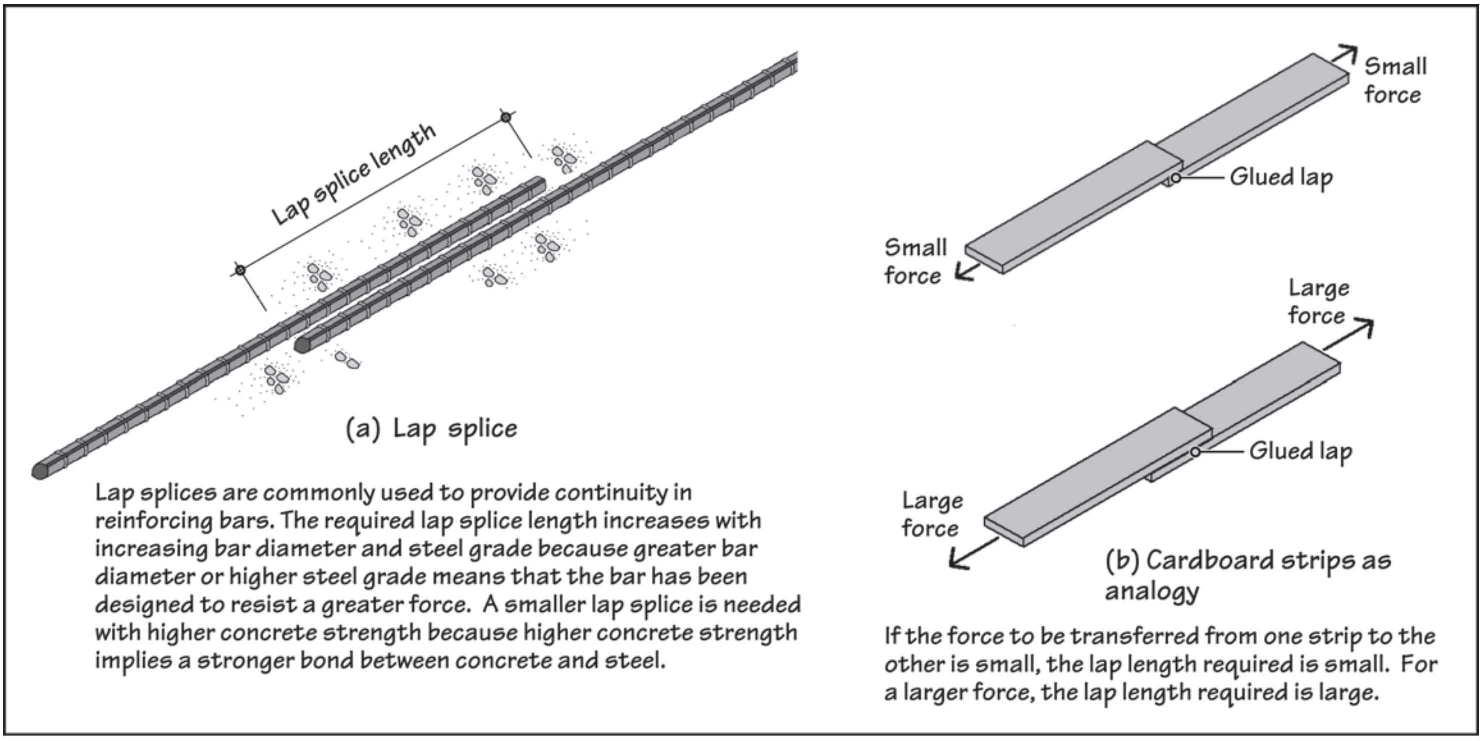
MECHANICAL COUPLERS FOR REINFORCING BARS

Lap splices are the most common means of splicing bars. However, they produce reinforcement congestion, which is problematic in heavily reinforced columns. Therefore, mechanical couplers are used to splice bars, Figure 22.22. Various types of proprietary couplers that have been tested for structural adequacy in gripping the bars from both ends are available.

USE OF HOOKED LONGITUDINAL BARS

For a reinforcing bar to develop the design tensile stress (60 ksi for Grade 60 steel), the bar must be embedded in concrete for a sufficient length. If the embedment length of the bar is inadequate, the bar will slip due to loss of anchorage, which may cause the member to fail.

Consider the simply supported beam in Figure 22.23. If the length of a bar from the point of maximum tensile stress (the beam's center in this case) to the end is inadequate, the bar will lose its anchorage, causing it to slip. To increase anchorage in such a case, hooks are provided at the ends of bars. If sufficient embedment length can be provided through straight bars, hooks are not needed. Thus, the provision of a hook is tantamount to increasing the



(a) Lap splice

Lap splices are commonly used to provide continuity in reinforcing bars. The required lap splice length increases with increasing bar diameter and steel grade because greater bar diameter or higher steel grade means that the bar has been designed to resist a greater force. A smaller lap splice is needed with higher concrete strength because higher concrete strength implies a stronger bond between concrete and steel.

(b) Cardboard strips as analogy

If the force to be transferred from one strip to the other is small, the lap length required is small. For a larger force, the lap length required is large.

FIGURE 22.19 Principles of lap splicing of reinforcing bars.

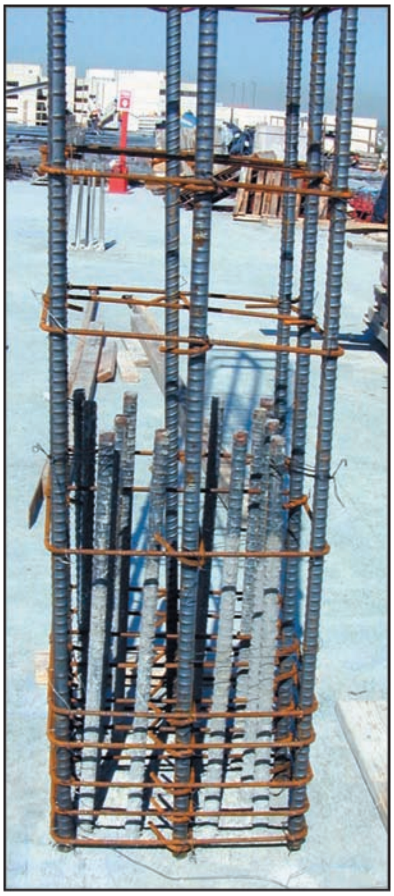


FIGURE 22.20 Lap splicing of column bars at the floor level. The lapped bars are generally placed adjacent to each other and tied together. A maximum spacing of 6 in. between lapped bars is, however, permitted by the American Concrete Institute (ACI) Code.

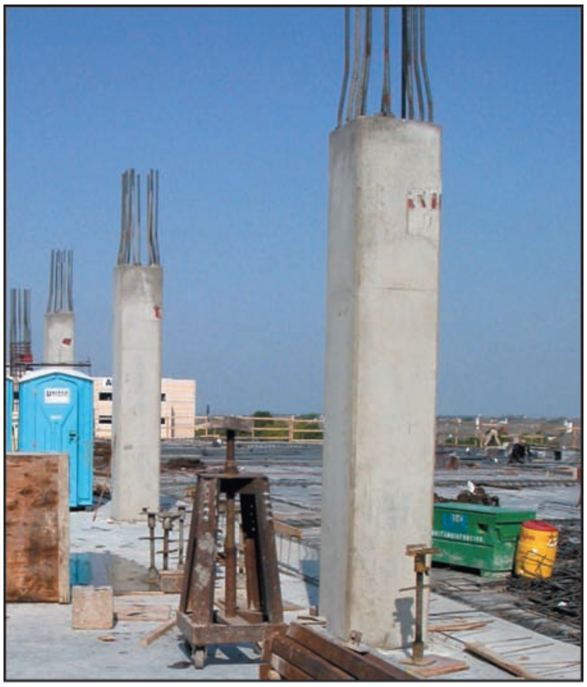


FIGURE 22.21 Column bars bent inward to receive bars for the upper floor.

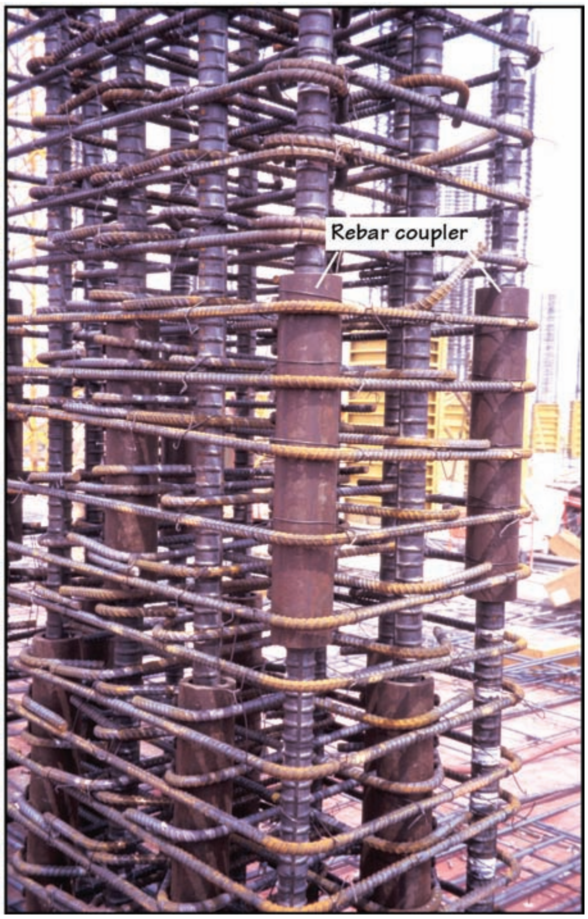


FIGURE 22.22 Reinforcement cage of a heavily reinforced-concrete column showing the use of couplers, instead of lap splicing of bars, to reduce congestion.

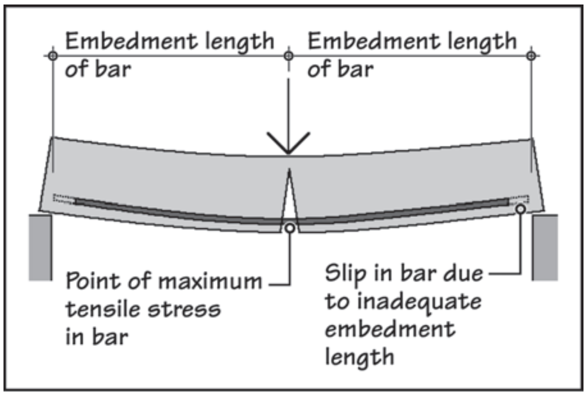

Embedment length of bar
Embedment length of bar
Point of maximum tensile stress in bar
Slip in bar due to inadequate embedment length

FIGURE 22.23 Bond failure of a bar due to inadequate embedment length.

embedment length of a bar. For bars used in a beam or slab, 90° or 180° hooks are used, Figure 22.24.

Hooks are generally required at the junction of a beam meeting the last column in a multicolumn bay because sufficient space is not available there for straight bars (Figure 22.18(b)). Note that hooks are effective only for bars in tension, not for bars in compression.

22.7 CORROSION PROTECTION OF STEEL REINFORCEMENT

To protect steel reinforcement from corrosion, a minimum amount of concrete cover is required. For reinforcement in footings, the minimum required cover is 3 in. For interior beams, the minimum cover required is 1.5 in., and exterior beams require a 2-in. cover, Table 22.1.

The cover is measured from the exposed concrete surface to the nearest edge of reinforcement. Therefore, in a beam, the cover is measured from the outer edge of stirrups (Figure 22.17), and in a column, from the outer edge of ties (Figure 22.27(b)).

To ensure the required cover in a beam or slab, bar supports are used. These are available in the form of either individual *chairs* or bolsters. Chairs may be of molded plastic, Figure 22.25(a), or of steel wire, Figure 22.25(b). Steel chairs have plastic-coated feet to prevent corrosion. A bolster is made from steel wire and several chairs, connected together in a long length. Both chairs and bolsters are available in various heights.

22.8 REINFORCEMENT AND FORMWORK FOR COLUMNS

The reinforcement in a column is provided primarily to resist compressive forces. However, because columns are also subjected to bending, the reinforcement must be located on the column periphery. Another reason for the peripheral location is that the reinforcement cage of a column confines the concrete within the cage, even after the concrete has been crushed to failure, resulting in a more gradual ductile column failure.

A column reinforcement cage consists of longitudinal reinforcement (vertical bars) and transverse reinforcement (ties), Figure 22.26. The total area of the longitudinal reinforcement for a column is based on structural requirements but must lie between 1% and 8% of the gross area of the column. Generally, however, it is difficult to accommodate a reinforcement area of more than 4% unless the bars are welded together at splices or coupled with mechanical couplers.

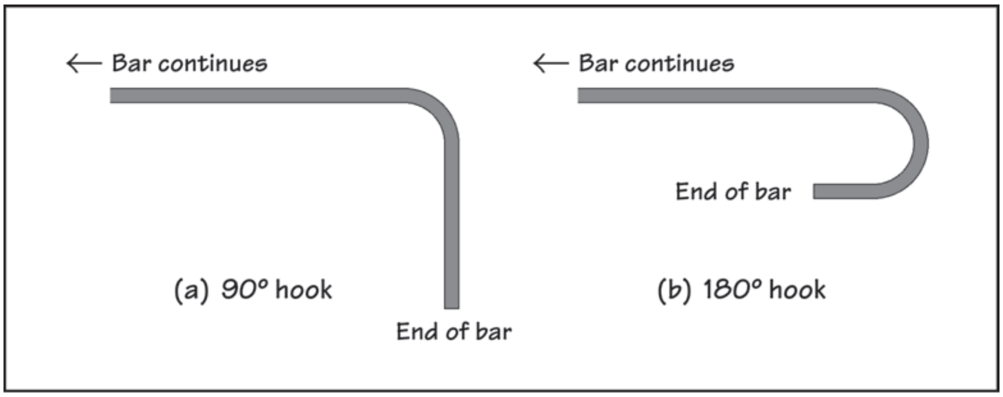


FIGURE 22.24 Note the 90° and 180° hooks in bars. Hook dimensions (diameter of the bend and extension of the bar from the bend to the end of the bar) have been standardized by the American Concrete Institute (ACI) Code so that both hooks have the same anchorage capacity and can be used interchangeably.

TABLE 22.1 MINIMUM CONCRETE COVER FOR REINFORCEMENT

Exposure of concrete	Minimum cover (in.)
Cast against and permanently exposed to earth	3.0
Exposed to earth or weather	2.0
Not exposed to earth or weather	
Beams and columns	1.5
Slabs and walls	0.75

Source: Building Code Requirements for Structural Concrete, ACI 318-05.

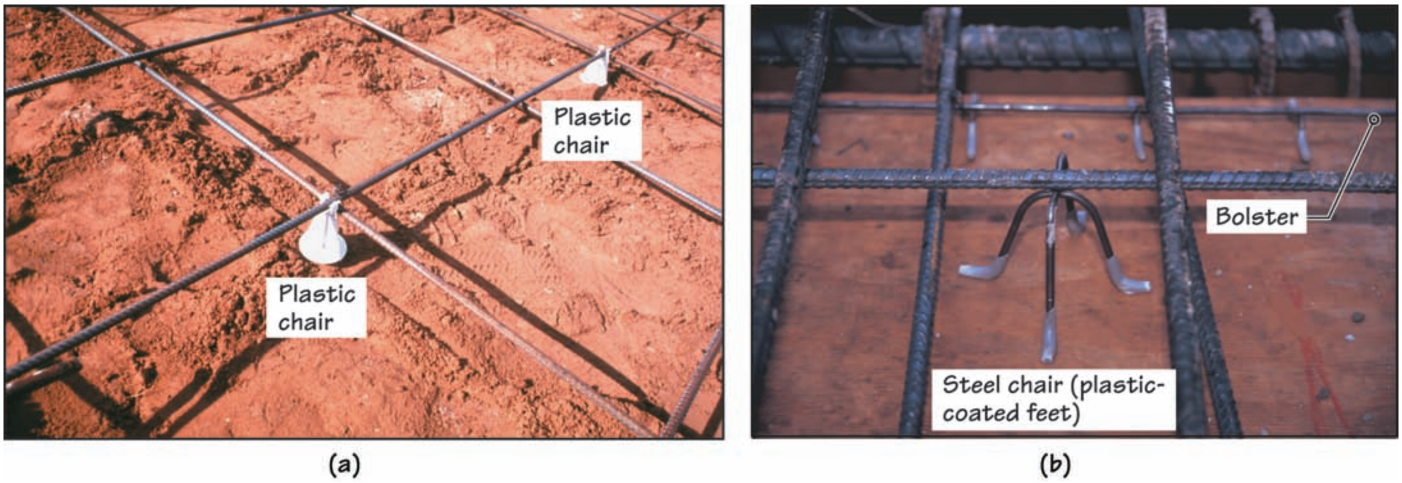


FIGURE 22.25 **(a)** Plastic chairs as bar support. Note that the bars from one direction are supported on chairs and the bars from the other direction are tied to the supported bars. **(b)** Chairs and bolsters as bar supports. A bolster is an assembly of several steel chairs joined together with a steel bar. Note that the steel chairs and bolsters have plastic-coated feet.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

14. Reshoring concrete structures are necessary where excessive deflection of floor slabs or foundation settlement is anticipated on removal of shores.
- **a.** True
- **b.** False

15. The structural design of formwork design is the responsibility of the
- **a.** general contractor.
- **b.** structural engineer.
- **c.** structural engineer, but the design must be approved by the building official.
- **d.** general contractor, but the design must be approved by the structural engineer.
- **e.** none of the above.

16. Form liners are used to
- **a.** ensure easy strippability of forms.
- **b.** allow acid etching of the concrete surface after stripping the forms.
- **c.** allow acid etching of concrete form before placing concrete.
- **d.** produce textured concrete surfaces.
- **e.** allow water washing of concrete after stripping the forms.

17. The primary purpose of steel reinforcement is to increase the tensile strength of concrete elements. However, steel reinforcement is also used to increase the shear strength and compressive strength of concrete elements.
- **a.** True
- **b.** False

18. Stirrups are used in a concrete beam
- **a.** to increase the beam's compressive strength.
- **b.** to provide tensile strength in the beam since concrete's tensile strength is negligible.
- **c.** to increase the tensile strength of the beam beyond that provided by concrete.
- **d.** to provide shear strength in the beam because concrete's shear strength is negligible.
- **e.** to increase the shear strength of the beam beyond that provided by concrete.

19. Stirrups are generally made of
- **a.** No. 3 or No. 4 bars.
- **b.** No. 4, No. 5, or No. 6 bars.
- **c.** No. 6 or No. 7 bars.
- **d.** bars of any diameter, as needed.

20. A doubly reinforced beam is one in which
- **a.** reinforcing bars are provided in bundles of two bars.
- **b.** reinforcing bars are provided at the top and bottom of the beam.
- **c.** reinforcing bars are provided in two layers at the bottom of the beam.
- **d.** reinforcing bars are provided in two layers at the top of the beam.
- **e.** none of the above.

(*Continued*)

PRACTICE QUIZ *(Continued)*

21. Mechanical couplers are used
- **a.** to lap splice reinforcing bars.
- **b.** as an economical alternative to lap splicing of reinforcing bars.
- **c.** where the lap-splice length of reinforcing bars is excessive.
- **d.** where lap splicing of reinforcing bars will produce excessive congestion.
- **e.** none of the above.

22. Hooks are used
- **a.** to lap splice reinforcing bars.
- **b.** where the lap-splice length is excessive.
- **c.** where lap splicing of bars will produce excessive congestion.
- **d.** all of the above.
- **e.** none of the above.

23. Hooks in bars are produced by turning the bars through
- **a.** 30° or 60°.
- **b.** 45° or 90°.
- **c.** 90° or 180°.
- **d.** 180° or 270°.

24. Steel reinforcement in concrete elements that are permanently exposed to the earth, such as in footings, must have a minimum concrete cover of
- **a.** 5 in.
- **b.** 4 in.
- **c.** 3 in.
- **d.** 2 in.
- **e.** 1 in.

25. The chairs used to support reinforcing steel bars are generally
- **a.** plastic chairs.
- **b.** steel-encased plastic chairs.
- **c.** steel chairs with plastic-coated feet.
- **d.** (a) and (b).
- **e.** (a) and (c).

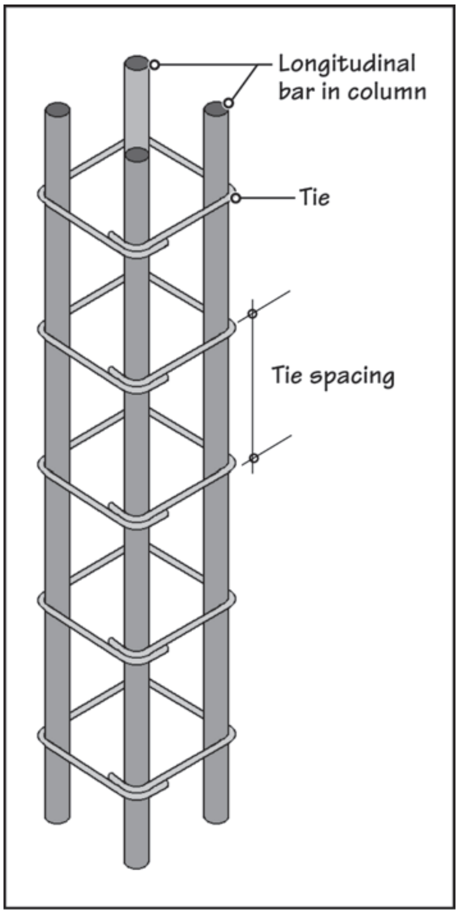


FIGURE 22.26 Reinforcement cage for a column consists of longitudinal bars and ties (transverse reinforcement). The minimum number of longitudinal bars in a square or rectangular column is four (as shown here). In a column with a larger number of bars, the tie pattern is more complex, as shown in Figure 22.27.

TRANSVERSE REINFORCEMENT IN COLUMNS—INDIVIDUAL TIES

Ties are similar to stirrups but have two structural functions. One is to prevent the buckling of the longitudinal reinforcement (which consists of slender bars under compression). If the bars are not prevented from buckling, they will burst out of the concrete. The other function is to provide shear resistance to columns subjected to bending. Ties also help in the formation of a reinforcement cage. Their center-to-center spacing is dictated by simple rules given in the American Concrete Institute (ACI) Code.

Ties are generally No. 3 or No. 4 bars. Each longitudinal column bar must be enclosed by a tie corner (see Figure 22.27(a) for an exception). Several tie shapes may be needed in the same column, Figure 22.27. In round columns, round ties may be used, Figure 22.28.

TRANSVERSE REINFORCEMENT IN COLUMNS—CONTINUOUS SPIRAL

In round columns, a continuous helical spiral may be used in place of individual ties. A column with transverse spiral reinforcement is more robust because of its greater ductility. That is why a column with spiral reinforcement is preferred in seismic zones. Continuous transverse spiral reinforcement may also be provided in square columns by using a circular reinforcement cage in place of a square cage.

COLUMN FORMS

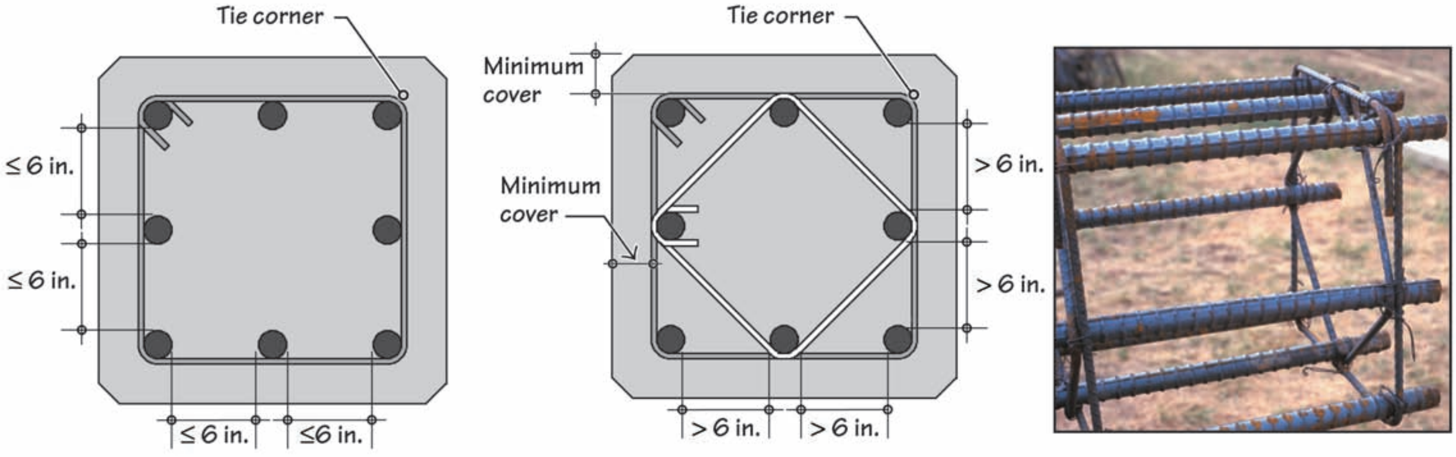
Column forms for rectangular or square columns are generally made of wood or steel. A typical column form consists of four panels braced by a steel angle frame on all sides. The angle frame is hinged at one end and clamped at the opposite end so that the form can be stripped by simply unclamping and rotating the unclamped side, Figure 22.29.

Round column forms may be of steel plate or waterproof fiberboard, Figure 22.30. Steel forms are reusable, and are generally semicircular and of short lengths that are bolted together to obtain the correct height. Fiber forms are one piece and meant for one-time use.

22.9 REINFORCEMENT AND FORMWORK FOR WALLS

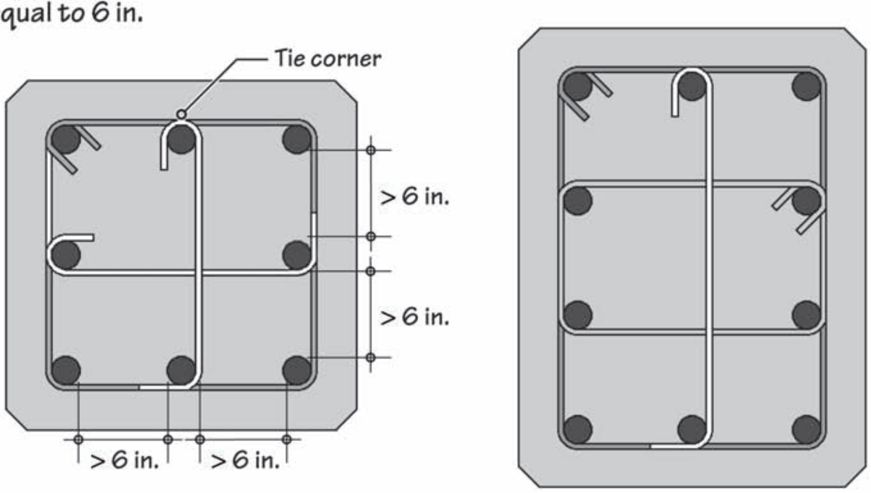
Concrete walls are commonly used in buildings as retaining walls, basement walls, shear walls, or load-bearing walls. The essential difference between the reinforcement in a wall and a column is that ties are not required in a wall unless the wall supports a large gravity load.

The reinforcement in a wall consists of a mesh formed by vertical and horizontal bars provided in one central layer. In a wall 10 in. or thicker, two layers of reinforcement are required close to each face of the wall, but separated from the face by minimum required cover, Figure 22.31.



(a) Tie arrangement in a square column with 8 longitudinal bars and one tie set. This arrangement can only be used if the clear space between a supported and an unsupported longitudinal bar is less than or equal to 6 in.

(b) Tie arrangement in a square column with 8 longitudinal bars and a set of two ties. See also (c)



(c) Tie arrangement in a square column with 8 longitudinal bars that uses a set of three ties—an alternative to the arrangement shown in (b)

(d) Tie arrangement in a rectangular column with 10 longitudinal bars and a set of three ties

Every longitudinal bar must be supported against buckling by a tie corner, as shown in (b), (c) and (d). However, if the clear distance between longitudinal bars is ≤ 6 in., an alternate bar may be left unsupported, as shown in (a).

A set of ties may consist of one tie shape, as shown in (a), a set of two ties, as shown in (b), a set of three ties, as shown in (c) and (d), etc.

The center-to-center spacing of the tie set is governed by empirical code requirements.

FIGURE 22.27 Tie arrangements in a typical rectangular or square reinforced-concrete column.

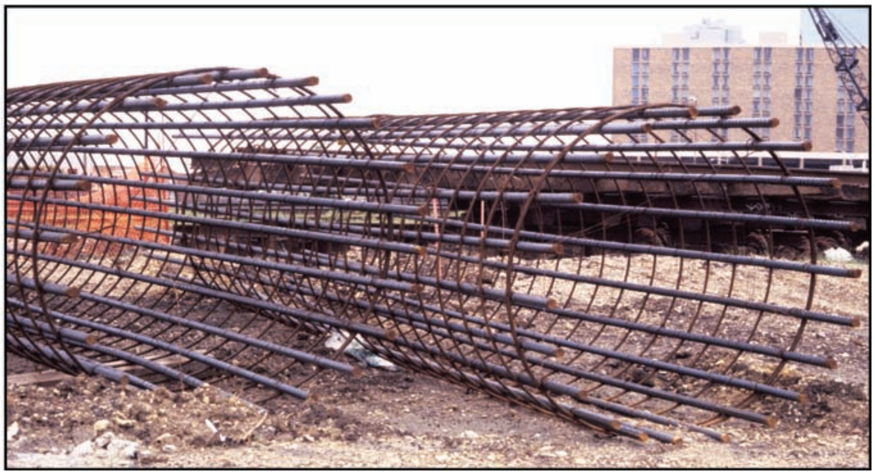
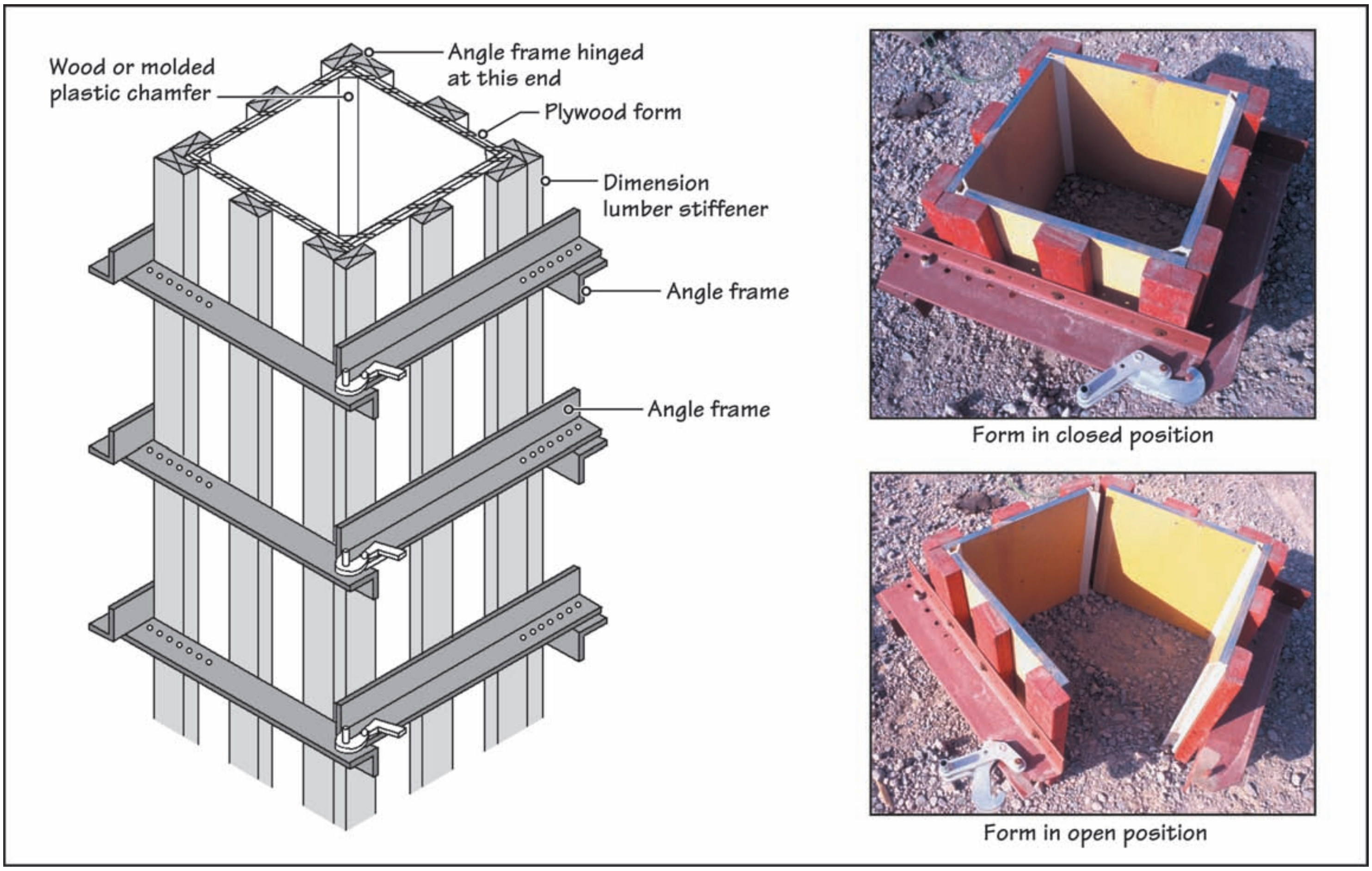


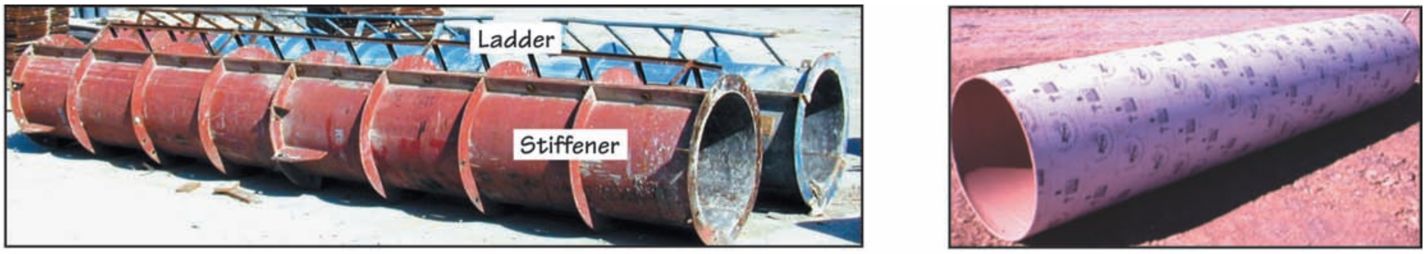
FIGURE 22.28 Reinforcement cage for a round column with circular ties.


Wood or molded plastic chamfer
Angle frame hinged at this end
Plywood form
Dimension lumber stiffener
Angle frame
Angle frame

Form in closed position

Form in open position

FIGURE 22.29 A typical rectangular or square column form. The photographs show a short section of a hinged column form in a formwork fabricator's yard. (Photo courtesy of Bensonwood Inc.)



(a) Reusable formwork for a concrete column made of 2-ft-long semicircular steel plates with end stiffeners that are bolted together at the stiffeners.

(b) One-time use fiberboard form for a round concrete column.

FIGURE 22.30 Two types of forms for round columns.

FORMWORK FOR WALLS

The formwork for each face of a wall is generally made of plywood panels (generally $\frac{3}{4}$ in. thick) supported by horizontal members (generally 2 × 4 lumber) called *walers*, Figure 22.32. The walers are supported by vertical lumber called *stiffbacks*. The stiffbacks are supported by diagonal braces, Figure 22.33. The formwork for each face is separated by *form ties*—specially shaped steel wires that separate and hold the formwork from two opposite faces and resist the pressure of wet concrete.

Form ties are available in various types. One commonly used type is a *snap tie*, which consists of a plastic cone and a loop at each end. The end-to-end distance between cones represents the wall thickness, Figure 22.34.

The wire of a snap tie under each cone has a narrow, brittle section that allows it to be snapped there by a plier-assisted twist of the end loop. The snapping is done after the formwork has been stripped. After removal of the end loops and the plastic cones, the pockets left by the cones are filled with a sealant.

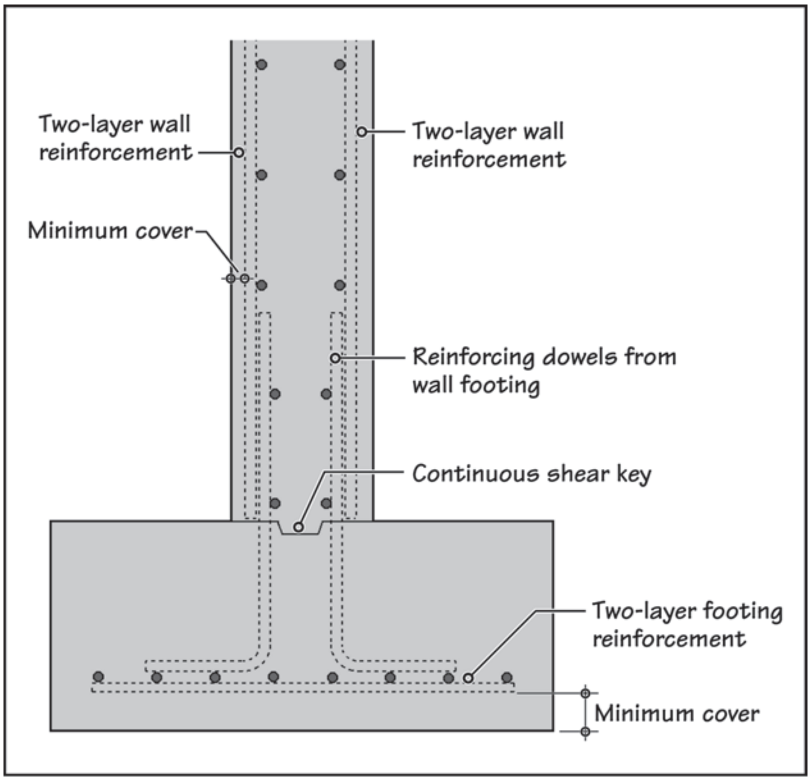

Two-layer wall reinforcement
Two-layer wall reinforcement
Minimum cover
Reinforcing dowels from wall footing
Continuous shear key
Two-layer footing reinforcement
Minimum cover

FIGURE 22.31 A section at the foundation level through a reinforced-concrete wall with two-layer reinforcement. Note that the footing of the wall is constructed first, with reinforcing dowels projecting out of the footing. (This is similar to construction of the footing for a column; see Expand Your Knowledge in Section 22.11.)

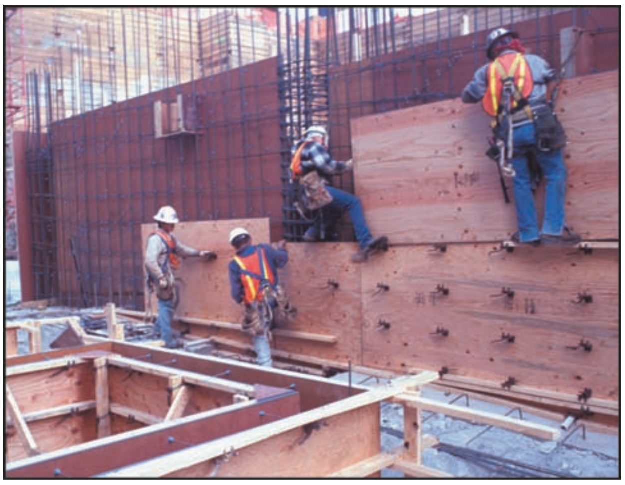


FIGURE 22.32 Workers equipped with safety harness erect the formwork for a reinforced-concrete wall. (See Figure 22.33 for details.)

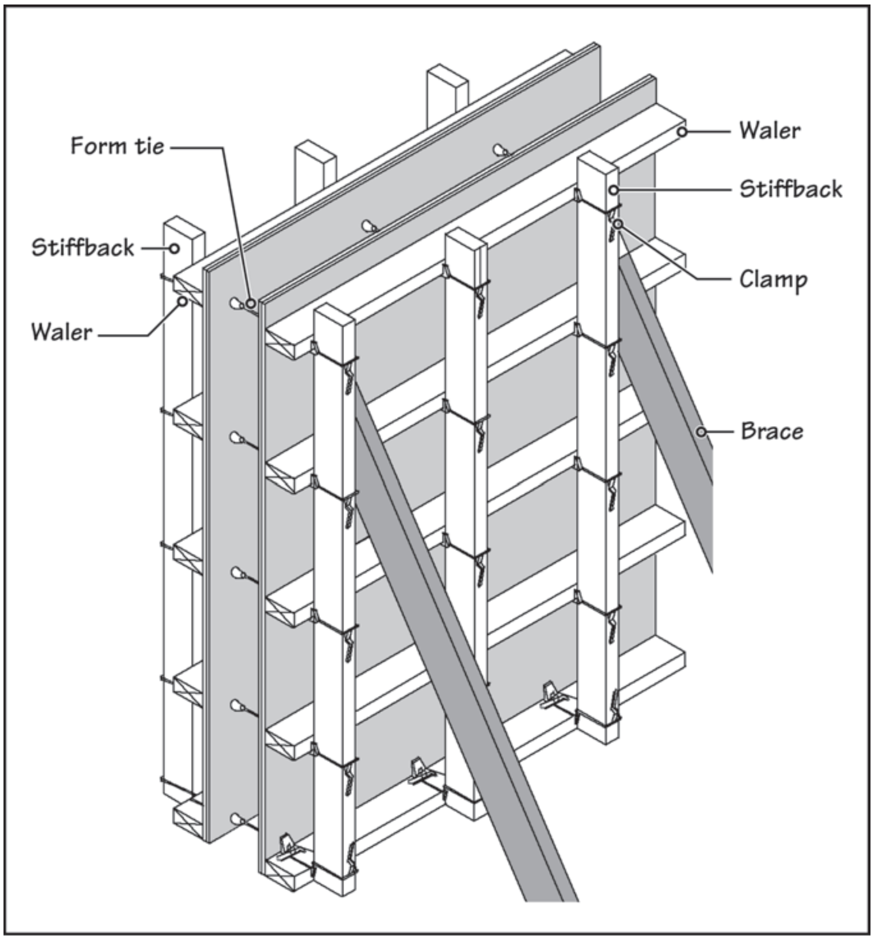

Form tie
Waler
Stiffback
Stiffback
Clamp
Waler
Brace

FIGURE 22.33 Isometric view of the formwork shown in Figure 22.32. Note that the formwork is made from plywood and dimension lumber. The entire assembly is fastened together with removable clamps. Form ties between opposite plywood panels separate the panels and hold them against the pressure of wet concrete.

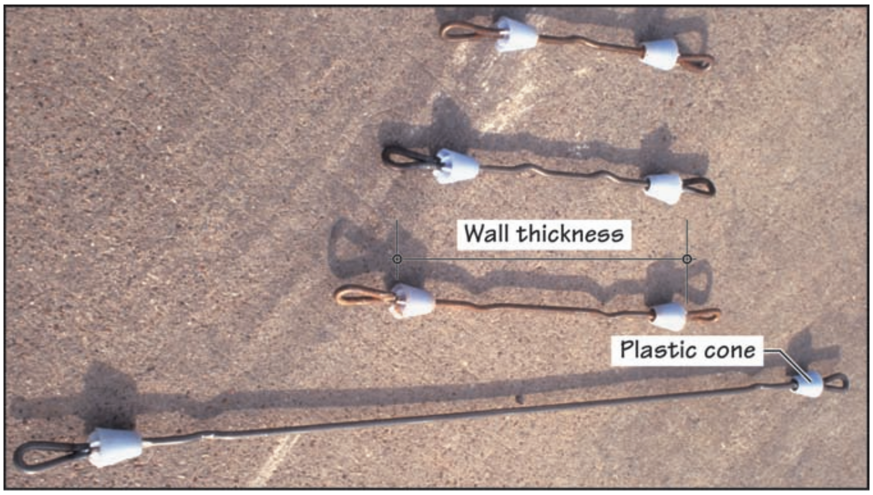


FIGURE 22.34 Snap ties are available in various sizes to suit various wall thicknesses. The out-to-out dimension between plastic cones represents the wall thickness. Several other form tie designs are available.

22.10 TYPES OF CONCRETE SLABS

As shown in Figure 22.35, site-cast concrete slabs can be of two types:

- *Ground-supported slabs* (also called *slabs-on-ground* or *slabs-on-grade*) bear directly on compacted ground (grade) with organic topsoil removed. Construction of concrete slabs-on-ground is covered in this chapter (Sections 22.11 and 21.12).
- *Elevated slabs* rest on and are part of the structural frame of the building. Therefore, they are also referred to as *framed slabs* or *suspended slabs*. Elevated concrete slabs are used at the second and higher floors of the building. However, where the soil conditions are unfavorable (or if the building has a basement), they are also used at the first (ground) floor. Construction of elevated slabs is covered in Chapter 23.

NOTE

Classification of Ground-Supported Slabs as Type I, II, or III

A classification of ground-supported concrete slabs similar to that mentioned in Figure 22.35 is given by the Building Research Advisory Board (BRAB). In this classification, isolated slabs are called *Type I* or *Type II*, respectively, depending on whether they are unreinforced or reinforced with nominal reinforcement. A ground-supported stiffened slab is called *Type III* [22.1].

GROUND-SUPPORTED CONCRETE SLABS

Ground-supported concrete slabs are further subdivided into:

- Isolated concrete slabs
- Stiffened concrete slabs

Isolated concrete slabs are those that are separated from the building's foundation with an isolation joint. A stiffened concrete slab is generally designed to function as a slab-and-foundation combination for wood light-frame (or light-gauge steel-frame) buildings and is particularly well suited for such buildings on expansive soils.

22.11 GROUND-SUPPORTED, ISOLATED CONCRETE SLAB

An isolated, ground-supported concrete slab is commonly used on stable, undisturbed soils (with all organic material removed) or on select fills compacted to provide a uniformly strong base. As long as the bearing capacity of the supporting ground is not too low, it is

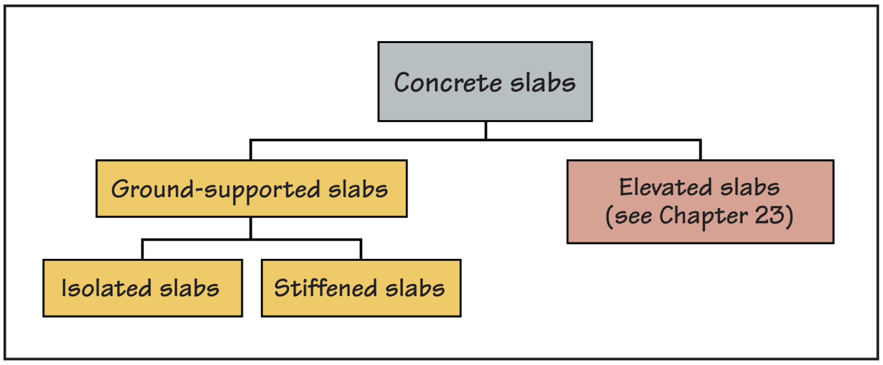


FIGURE 22.35 Types of concrete slabs.

generally not a critical issue because concrete slabs are fairly rigid. Therefore, concentrated loads on the slab (from foot traffic, moving furniture, forklifts, and other items) are spread over a large area. Consequently, the stress on the ground due to the loads on the slab is relatively small.

Vapor Retarder

A vapor retarder (generally a 6-mil-thick polyethylene sheet with lapped joints) is placed immediately below an isolated slab. It prevents the passage of subsoil water and water vapor through the slab into the building's interior. In the absence of a vapor retarder, the vapor from below the slab may condense under an object covering the slab, such as a rug, furniture legs, or boxes.

A vapor retarder is particularly important if the interior of the building is heated or cooled and/or if the slab is covered with a vapor-impermeable floor finish such as vinyl tiles, linoleum, or thin-set terrazzo. A vapor retarder is not required under a slab if the passage of water vapor does not affect the building's interior, such as a garage or an open shed. It is also not required under driveways, pavements, or patios, for example.

A secondary advantage of a vapor retarder is that it works as a slip membrane between the slab and the subbase so that the slab moves more freely as it shrinks. In the absence of a slip membrane, the shrinkage of the slab is restrained, which induces tensile stresses in the slab. These stresses are in addition to the tensile stresses caused by shrinkage. Because the reinforcement in an isolated slab-on-ground is provided to resist shrinkage stresses, a vapor retarder reduces reinforcement requirements.

A disadvantage of using a vapor retarder is that it aggravates the differential shrinkage between the top and bottom of the slab. Water is lost by evaporation from the top of the slab but remains relatively intact at the bottom, leading to dishlike curling of the slab at the edges, Figure 22.36. Curling can be reduced by using concrete with a low water-cement ratio and proper curing to ensure the availability of sufficient moisture at the top of the slab.

Subbase as the Drainage Layer

A subbase—a layer of granular material placed immediately above the top of compacted ground (below the vapor retarder, if used)—is generally required. Although a properly placed and consolidated concrete slab is resistant to infiltration of subsoil water, a subbase provides additional protection by providing a capillary break. The subbase also equalizes slab support by filling any uneven spots in the ground.

The required subbase thickness is generally 4 in. A thicker subbase does not yield greater benefit. Subbase material can be crushed stone, gravel, or sand. Sand is preferred in slabs provided with a vapor retarder because, unlike crushed stone or gravel, it does not puncture the vapor retarder.

Concrete Strength and Thickness

A concrete strength of 3,000 psi for residential slabs and 4,000 psi for commercial and light-industrial slabs is generally recommended. A higher strength is needed only for more heavily loaded slabs or where greater wear resistance is needed. The thickness of an isolated reinforced-concrete slab is also a function of the load it must carry, with a typical minimum of 4 in.

Amount of Steel Reinforcement

A concrete slab supported on stable, compacted soil may not require steel reinforcement. However, a small (i.e., nominal) amount of reinforcement is generally provided in an isolated slab, Figure 22.37. Its purpose is to reduce the size of shrinkage cracks in the slab.

Note that reinforcement does not prevent the slab from cracking, but it reduces the width of each individual crack, keeping the overall crack width unaffected. Note also that reinforcement does not increase the load-carrying capacity of the slab, which is primarily a function of slab thickness. Because the size of individual cracks is reduced, control joints can be spaced farther apart in a reinforced slab than in an unreinforced slab. It follows, therefore, that if control joints in a slab are unacceptable, the slab must be provided with a greater amount of reinforcement.

NOTE

The Terms *Grade* and *Ground*

The terms *grade* and *ground* are generally used interchangeably. Thus, *slab-on-ground* and *slab-on-grade* imply the same thing. However, *slab-on-ground* is more commonly used in the literature published by the American Concrete Institute (ACI), Portland Cement Association (PCA), and Post-Tensioning Institute (PTI).

By contrast, terms such as *natural grade, existing grade, finished grade, compacted grade, above grade, below grade, grade beams, grading lines* (contour lines), and so on, are in common use.

NOTE

Fibrous Concrete Reinforcement in Slabs-on-Ground

Because the purpose of reinforcement in an isolated concrete slab-on-ground is to control shrinkage cracks, synthetic (polypropylene, nylon, and polyester) fibers are being increasingly used as replacement for steel reinforcement. They are mixed with other concrete ingredients.

Synthetic fibers are generally 0.5 in. to 1.5 in. (12 to 38 mm) long and approximately 0.04 in. (1 mm) thick. Shorter fibers are effective during the early stages of concrete hardening, and the longer fibers increase the tensile strength of hardened concrete. Fiber-reinforced concrete is generally more economical than hand-tied steel bars.

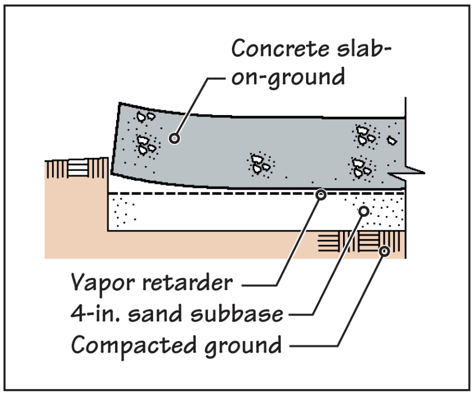


FIGURE 22.36 Curling of a concrete slab-on-ground due to differential drying shrinkage.

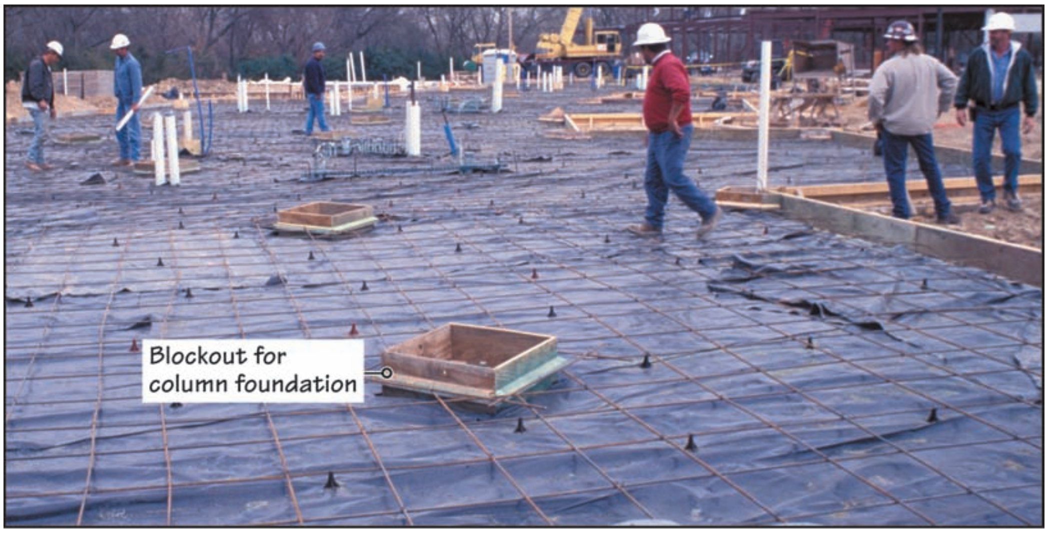


FIGURE 22.37 An isolated slab being inspected before concreting. Observe the vapor retarder and the reinforcing bars supported on chairs. Also observe the blockouts for columns, which isolate the slab from the building's structure.

LOCATION OF STEEL REINFORCEMENT IN AN ISOLATED SLAB

Because the purpose of reinforcement in an isolated, ground-supported concrete slab is to control shrinkage cracks, it should be located as close to the top of the slab as possible, keeping in view the requirements for cover and surface finish.

JOINTS IN AN ISOLATED CONCRETE SLAB-ON-GROUND

An isolated concrete slab-on-ground requires the following types of joints:

- Control joints
- Isolation joints
- Construction joints

CONTROL JOINTS

Control joints accommodate the shrinkage of concrete. Their purpose is to provide weakness in the slab at predetermined locations to force the slab to crack there. In the absence of control joints, the slab will crack in a random, haphazard pattern. Control joints are generally provided by sawing the slab at intervals to a depth of 0.25 times the thickness of the slab, Figure 22.38. The width of a saw-cut joint is approximately $\frac{1}{8}$ in.

Because concrete begins to shrink and crack as it hardens, the slab must be cut as soon as it is hard enough to provide a clean, unraveled joint (usually within 48 h of concrete placement). Control joints are spaced at 24 times the thickness of slab in both directions, but not more than 15 ft apart. (In exterior concrete walkways and pavements, control joints may be provided through saw-cut joints or tooled joints. A tooled joint is a shallow groove made while the concrete is green.)

The crack that develops under a control joint follows a zigzag pattern along the boundaries of coarse aggregate particles. The zigzag crack, shown in Figure 22.38, provides shear interlock between adjacent sections of the slab, referred to as *aggregate interlock*.

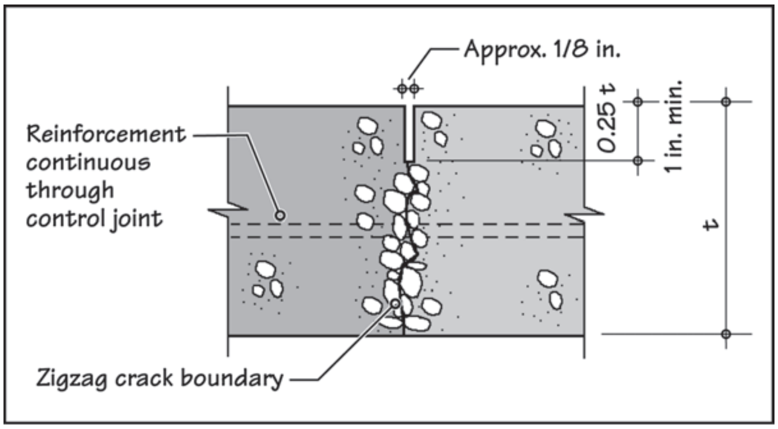
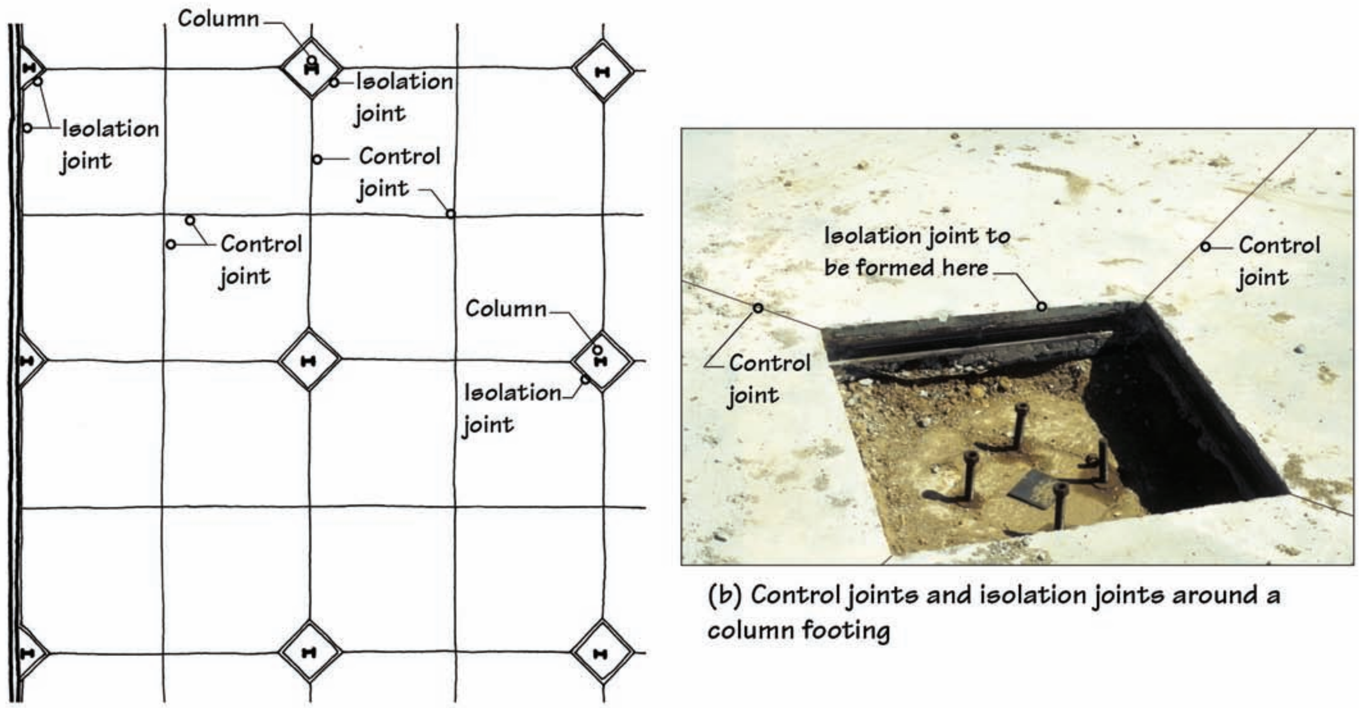


FIGURE 22.38 Section through a control joint in a slab. The slab generally cracks through its entire thickness under a control joint. Shear transfer between adjacent sections of the slab at a control joint is provided by the zigzag crack along aggregate boundaries.

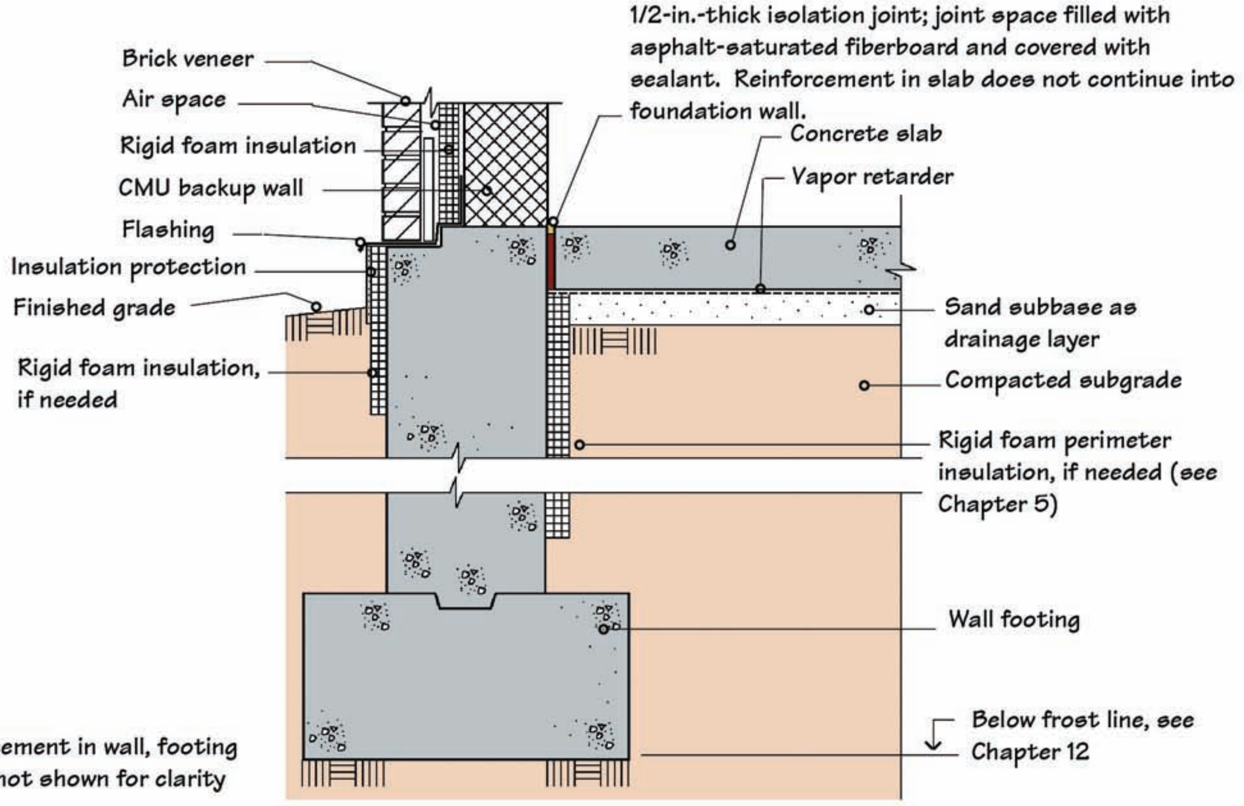
ISOLATION JOINTS

Unlike control joints, *isolation joints* in a concrete slab extend the entire thickness of the slab. They are typically $\frac{1}{2}$ in. wide and are provided to ensure that the slab is isolated from the building's structural components so that their movement (creep, foundation settlement, etc.) is not transferred to the slab. The joint space is generally filled with asphalt-saturated fiberboard and covered with a sealant. Figure 22.39 shows the location of control joints and isolation joints in a typical isolated interior slab.


Column
Isolation joint
Isolation joint
Control joint
Control joint
Column
Isolation joint
Isolation joint to be formed here
Control joint
Control joint

(a) Layout of control joints and isolation joints in a concrete slab-on-ground

(b) Control joints and isolation joints around a column footing


1/2-in.-thick isolation joint; joint space filled with asphalt-saturated fiberboard and covered with sealant. Reinforcement in slab does not continue into foundation wall.
Brick veneer
Air space
Rigid foam insulation
CMU backup wall
Flashing
Insulation protection
Finished grade
Rigid foam insulation, if needed
Concrete slab
Vapor retarder
Sand subbase as drainage layer
Compacted subgrade
Rigid foam perimeter insulation, if needed (see Chapter 5)
Wall footing
Below frost line, see Chapter 12
Reinforcement in wall, footing or slab not shown for clarity

(c) Typical section at the junction of a load-bearing wall and an isolated concrete slab

FIGURE 22.39 Isolation joints and control joints in an interior isolated concrete slab-on-ground.

EXPAND YOUR KNOWLEDGE

Other Examples of Construction Joints

Another example of a commonly used construction joint is the joint between a concrete column and its footing, Figure 1. Practical considerations require that the footing must be constructed first; after the concrete in the footing has hardened, the formwork for the column is erected. Subsequently, the concrete for the column is placed.

Additional construction joints in a column are placed between the top of the column and the bottom of the beam or slab that rests on the column. These joints are not visible and, therefore, do not need any aesthetic treatment.

Horizontal construction joints in a concrete wall must, however, be provided with a relief joint because (a) it is difficult to match colors between two concrete placements and (b) the top surface of the lower concrete may not be perfectly level, resulting in an irregular construction line, or it may be slightly out of plane with the adjacent concrete. A relief joint creates a shadow line on the surface and helps to obscure the visual imperfections of the joint, Figure 2.

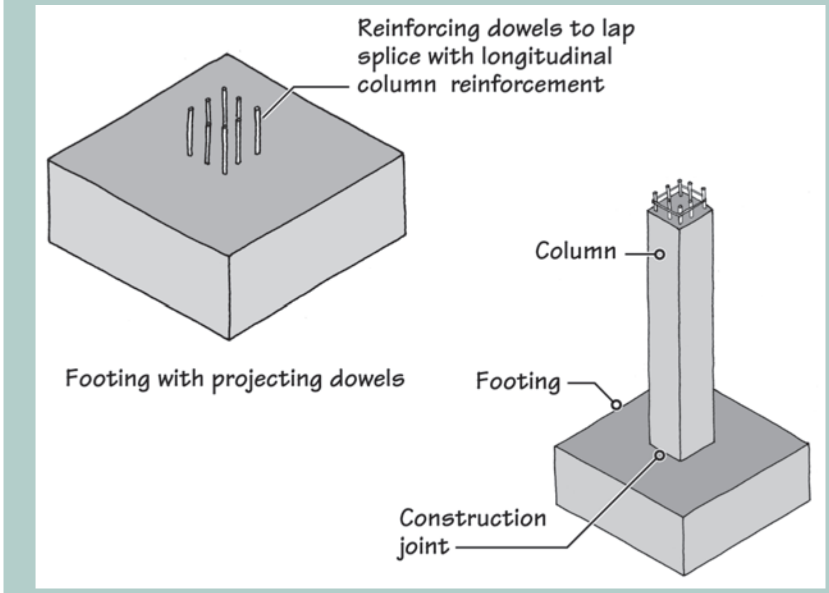

Reinforcing dowels to lap splice with longitudinal column reinforcement
Column
Footing with projecting dowels
Footing
Construction joint

FIGURE 1 Construction joint between a column and its footing.

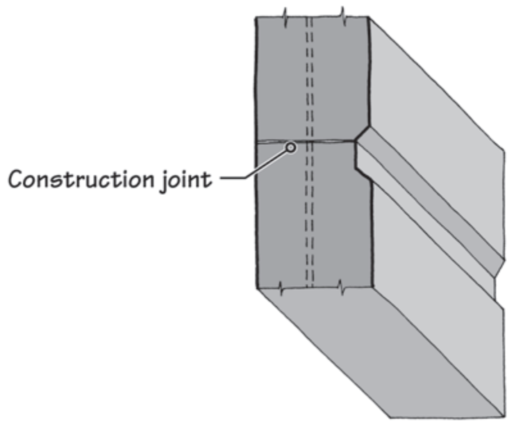


FIGURE 2 Horizontal construction joint in a concrete wall.

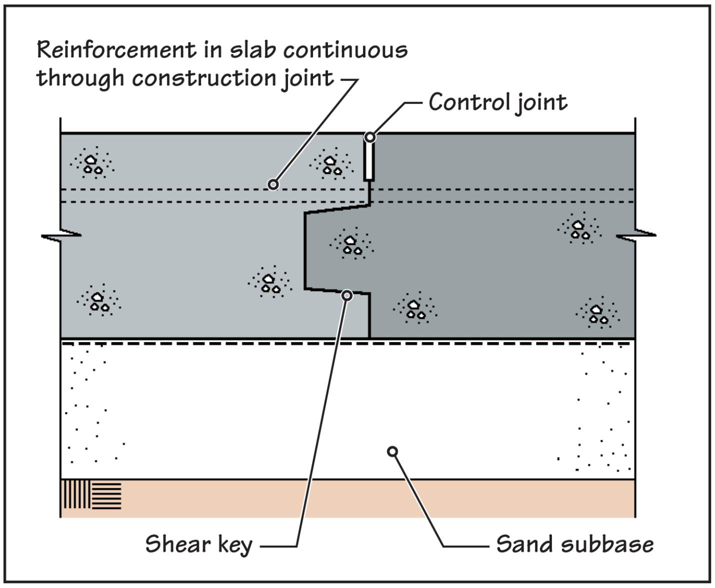


FIGURE 22.40 Detail of a keyed construction joint. A keyed control joint is generally provided at a construction joint in a slab-on-ground.

CONSTRUCTION JOINTS

A *construction joint* (also called a *cold joint*) is a nonmovement joint in a large concrete slab. This is used when the concrete cannot be placed in one continuous operation. The time interval between two concrete placements may be a few hours or several days.

A construction joint is detailed as if the component is monolithic across the joint. In other words, the reinforcement goes through the joint undisturbed. However, if the interval between the concrete placements is long, the surface of contact is cleaned with a stiff wire brush before the next batch is placed. This improves the bond between the two placements, enhancing the monolithicity between them.

A shear key is generally provided at a construction joint in a slab, which distributes the load across the joint, Figure 22.40. The shear key prevents vertical differential movement of adjacent slab sections, similar to that provided by aggregate interlock across a control joint.

22.12 GROUND-SUPPORTED, STIFFENED CONCRETE SLAB

A ground-supported, stiffened concrete slab is similar to an isolated concrete slab, except that the slab is stiffened with perimeter and interior beams (ribs) in both directions, forming a *ribbed concrete slab*. It is often used as a slab-and-foundation combination for wood light-frame (or light-gauge steel-frame) buildings. The ribs not only contribute to the stiffness of the slab, but also function as footings for load-bearing walls.

A stiffened slab is designed to withstand loads without excessive deflection even when it loses ground support at some locations. It is, therefore, well suited as a slab-and-foundation combination for light-frame buildings on soils subjected to swelling and shrinkage, so that the slab moves up and down uniformly with movement of the ground. Inadequate stiffness of the slab can produce differential movement, which can produce cracking in brittle elements supported by the slab, such as masonry walls, or gypsum board.

A stiffened slab-on-ground can be designed as one of the following:

- Ribbed reinforced-concrete slab (i.e., with reinforcing bars)
- Ribbed posttensioned (PT) concrete slab (i.e., with prestressing steel)

A PT slab is more commonly used because of its relative economy and the reduction in the size and number of cracks. Additionally, a PT slab generally does not require control joints. The construction of a PT slab is discussed here in detail. However, the principles of constructing a ribbed, reinforced slab-on-ground are identical to those of a ribbed, PT slab-on-ground except for the difference in the type of steel used. However, a PT slab requires greater skill and technology for construction. Additionally, if a hole is to be cut into a PT slab after its construction, it must be ensured that a prestressing tendon is neither cut nor damaged by it.

PRESTRESSING TENDONS AND THEIR LAYOUT

Figure 22.41 shows a typical PT slab during concrete placement. The prestressing tendons typically consist of an individual $\frac{1}{2}$-in.-diameter, seven-wire strand called a *monostrand* (multistrand tendons are used in some elevated slabs). The strand is coated with corrosion-inhibiting grease and encased in an extruded plastic sleeve (sheathing), Figure 22.42.

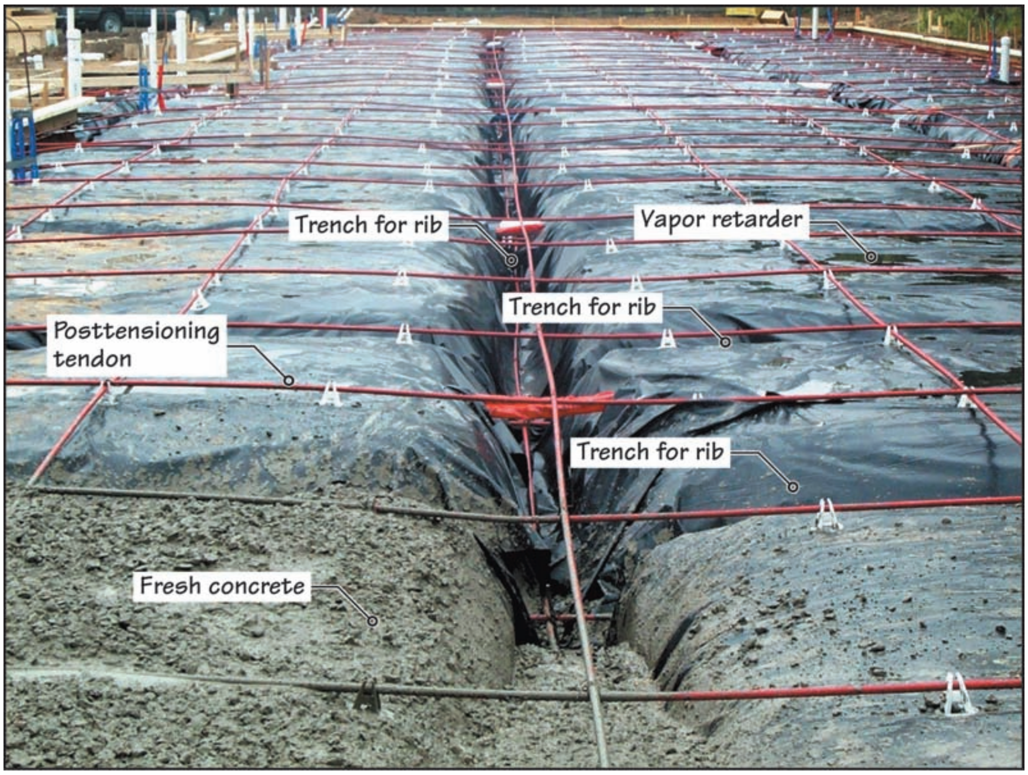


FIGURE 22.41 A PT concrete slab during concrete placement. Observe the prestressing tendons supported by plastic chairs and a vapor retarder that runs continuously under the slab. Observe the provision of ribs in both directions. Note that the tendons placed at the bottom of the ribs are transitioned up at the ends.

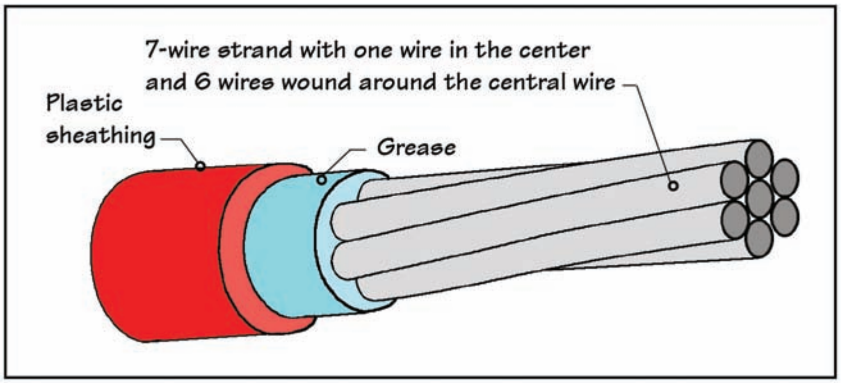

7-wire strand with one wire in the center and 6 wires wound around the central wire
Plastic sheathing
Grease

FIGURE 22.42 Anatomy of a single strand (called, *monostrand*) prestressing steel.

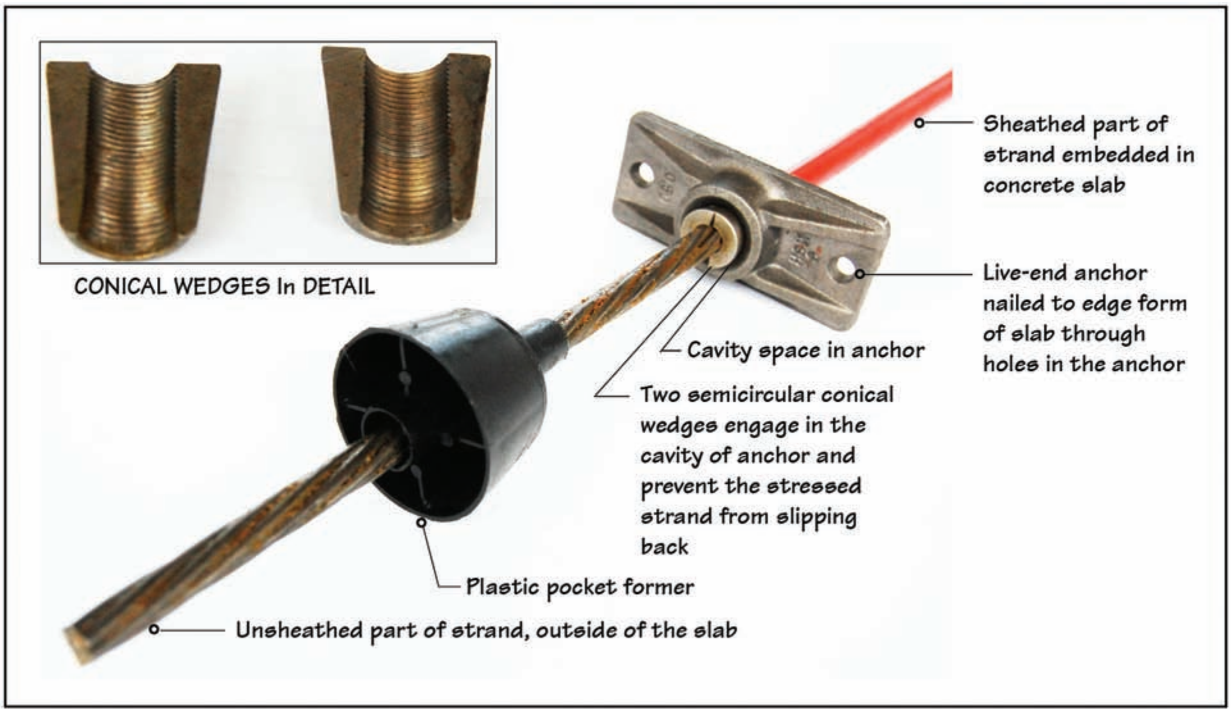

CONICAL WEDGES In DETAIL
Sheathed part of strand embedded in concrete slab
Live-end anchor nailed to edge form of slab through holes in the anchor
Cavity space in anchor
Two semicircular conical wedges engage in the cavity of anchor and prevent the stressed strand from slipping back
Plastic pocket former
Unsheathed part of strand, outside of the slab

FIGURE 22.43 Anatomy of a live-end anchor. A dead-end anchor is similar. A pocket former is not needed in a dead-end anchor, see Figure 22.45.

Each tendon has two anchor assemblies, one at each end. One end has a fixed anchor assembly called a *dead end*. The opposite end has the stressing-end assembly, called a *live end*. The tendon is stressed from the live end. Dead-end and live-end anchors are almost identical. The anchor contains a cavity to accommodate two semicircular conical steel wedges that prevent the stressed tendon from slipping back, Figure 22.43.

The only difference between a live end and a dead end is that the live-end anchor is provided with a plastic pocket former, which gets embedded in concrete. The pocket former is removed before stressing of the tendons and grouting of the pocket, as described later.

A PT ribbed slab-on-ground is typically 4 in. to 5 in. thick. The ribs are typically 10 in. to 12 in. wide and 24 in. to 36 in. deep, spaced a maximum of 10 ft to 15 ft on center.

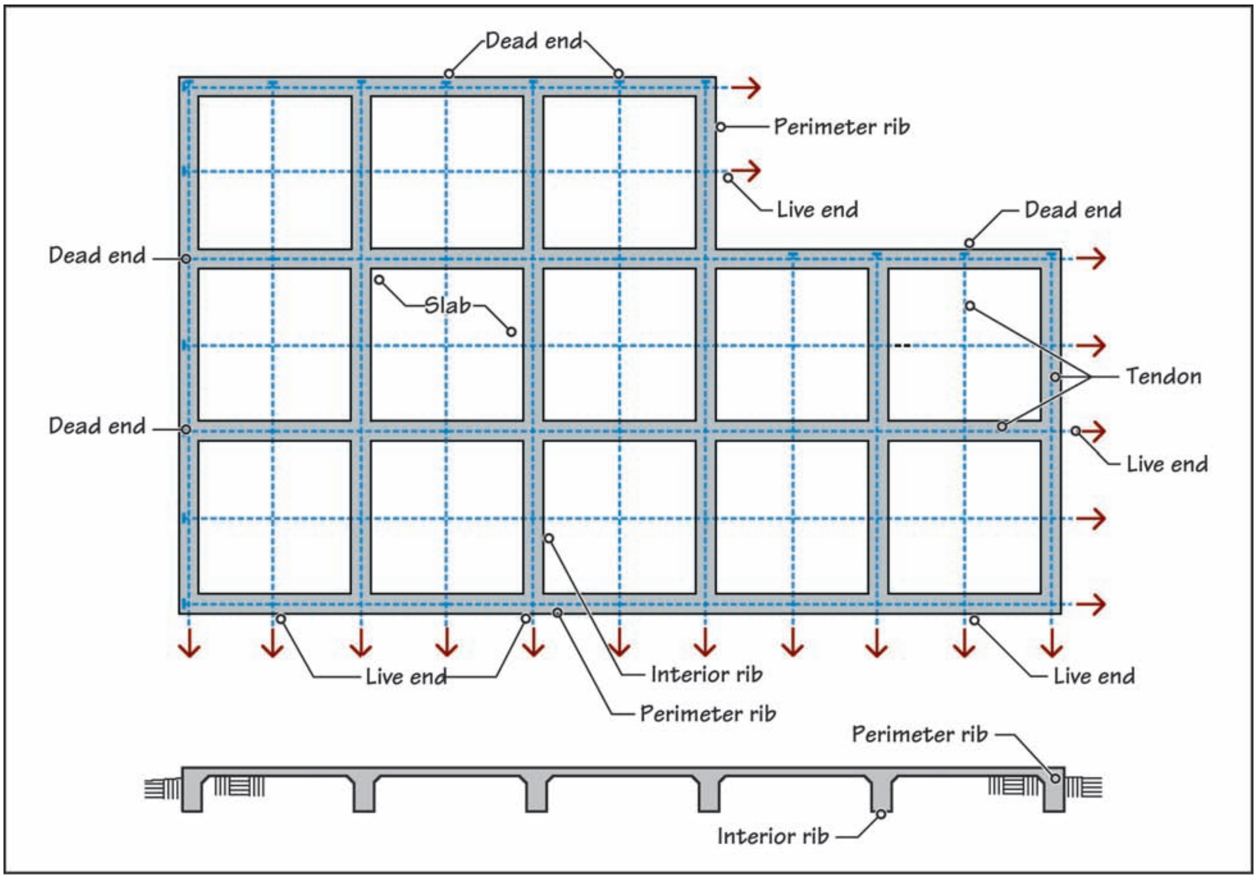

Dead end
Perimeter rib
Live end
Dead end
Dead end
Slab
Tendon
Dead end
Live end
Live end
Interior rib
Perimeter rib
Live end
Perimeter rib
Interior rib

FIGURE 22.44 Plan and section of a typical PT slab-foundation combination showing the layout of ribs and prestressing tendons.

Figure 22.44 shows the plan and section of one such slab, and Figure 22.45 shows the details of dead-end and live-end anchors.

STRESSING OF TENDONS

A concrete strength of 3,000 psi is generally used for a PT slab. The concrete is placed, vibrated, finished, and cured in the same way as for any other slab. After the concrete has hardened (generally 24 to 48 h after its placement), the edge forms from the slab are removed. This allows easy removal of pocket formers while the concrete is still green.

The tendons are stressed after the concrete has gained sufficient strength (approximately 2,000 psi). However, stressing should not be delayed excessively to forestall the development of shrinkage cracks in the slab. Generally, an interval of 3 to 10 days is used between concrete placement and stressing, depending on factors such as ambient temperature, water-cement ratio of concrete, and admixtures used in concrete.

The prestressing equipment consists of a jack connected to a hydraulic pump, Figures 22.46 and 22.47. The effective compressive prestress introduced in the slab is 50 psi to 100 psi, which is determined by the gauge readings on the pump and verified by measuring

NOTE

Ribbed Slab versus Constant-Thickness Slab

A constant-thickness PT slab-on-ground is often used in place of a ribbed PT slab-on-ground. Referred to as a *California slab*, it is 7.5 in. or thicker (without any beams). Another version of a constant-thickness slab is a 5-in.-thick slab with perimeter beams and no intermediate beams.

Source: *Engineering News-Record* (http://www.enr.com), September 20, 2004, p. 8.

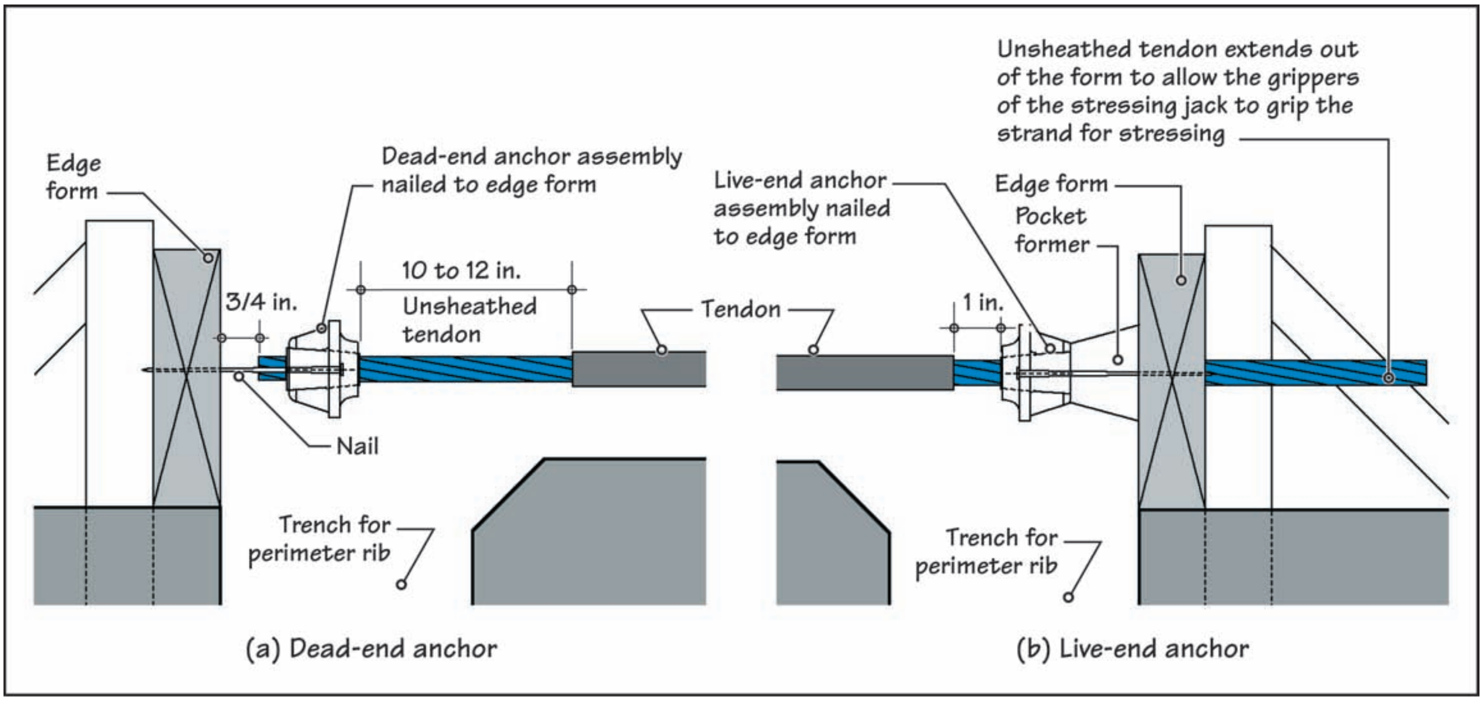

Edge form
Dead-end anchor assembly nailed to edge form
3/4 in.
10 to 12 in.
Unsheathed tendon
Tendon
Nail
Trench for perimeter rib
(a) Dead-end anchor
Unsheathed tendon extends out of the form to allow the grippers of the stressing jack to grip the strand for stressing
Live-end anchor assembly nailed to edge form
Edge form
Pocket former
1 in.
Tendon
Trench for perimeter rib
(b) Live-end anchor

FIGURE 22.45 Details of a dead-end and a live-end anchor.

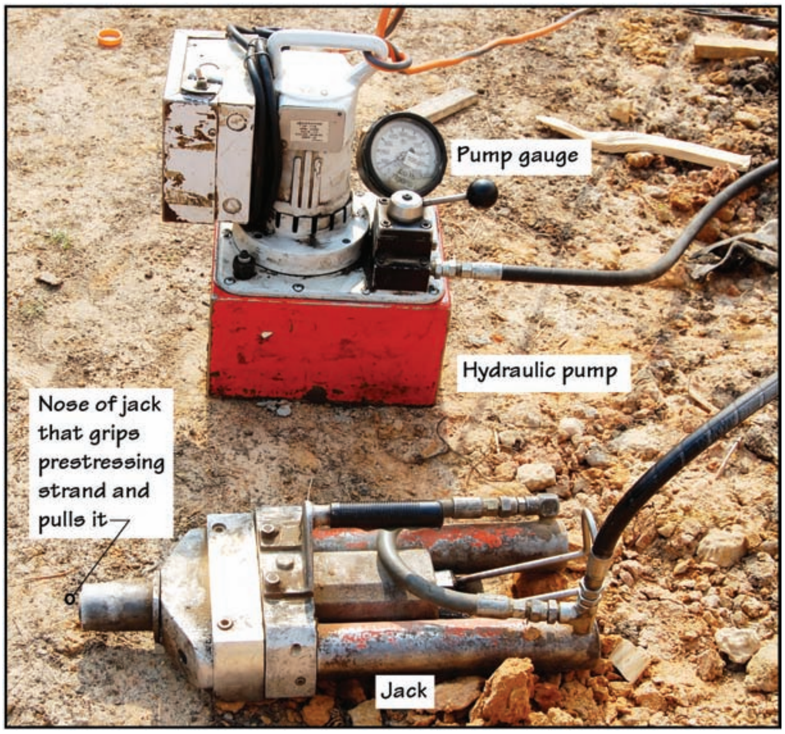

Pump gauge
Hydraulic pump
Nose of jack that grips prestressing strand and pulls it
Jack

FIGURE 22.46 The prestressing equipment consists of only two items—a jack that is connected to a hydraulic pump. The nose piece of jack grips the prestressing strand and pulls it, as shown in Figure 22.47. The gauge reading provides the amount of prestressing force induced in the strand.

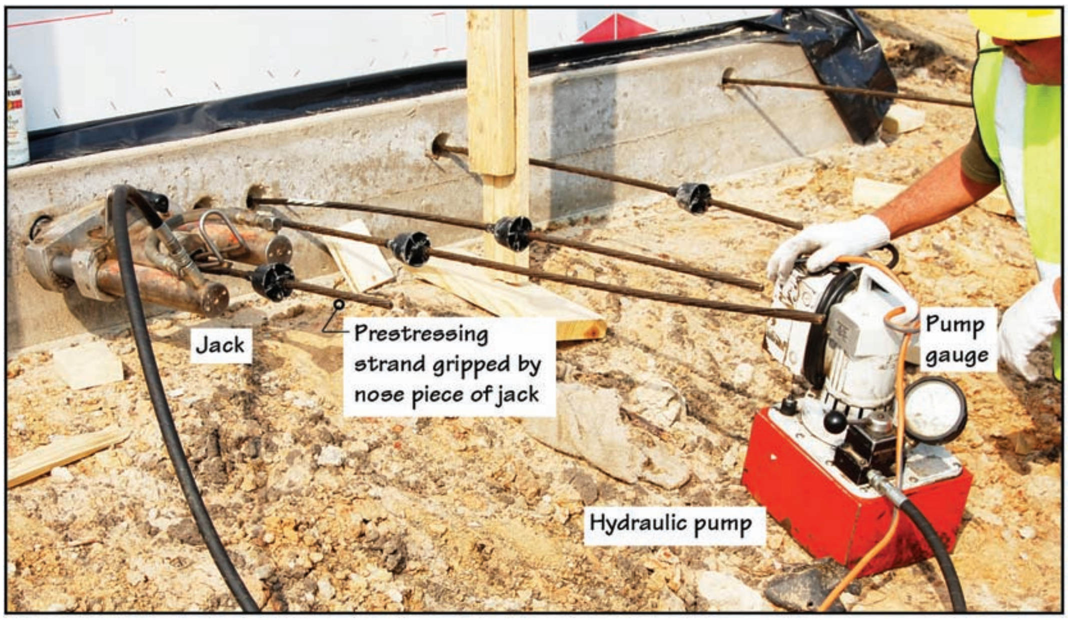


FIGURE 22.47 Prestressing operation. After the nose of the jack is engaged with the prestressing strand, the pump is switched on until the required prestressing force is achieved as given by the pump gauge, which is subsequently verified by measuring the elongation of the strand, see Figure 22.48.

the elongation in tendons after stressing. Therefore, before stressing begins, each tendon is reference marked with paint at the live end at a constant distance from the slab edge, Figure 22.48.

After the tendon has been tensioned by the required force, the excess length of tendon is either saw-cut or flame-cut, and the pocket left by the pocket former is patched with non-shrink grout, Figure 22.49.

POSTTENSIONED SLAB-ON-GROUND TO ELIMINATE CONTROL JOINTS

Although posttensioned, ground-supported slabs are generally used as a slab-foundation combination, they are also used in situations where they do not function as foundations, such as where control joints are unacceptable and the cracking of the slab is to be minimized. In such a slab, posttensioning of the slab is done in two stages. The first stage of posttensioning is done within 36 h to 48 h of concrete placement to prevent any initial cracking of the slab, followed by the second stage a few days later.

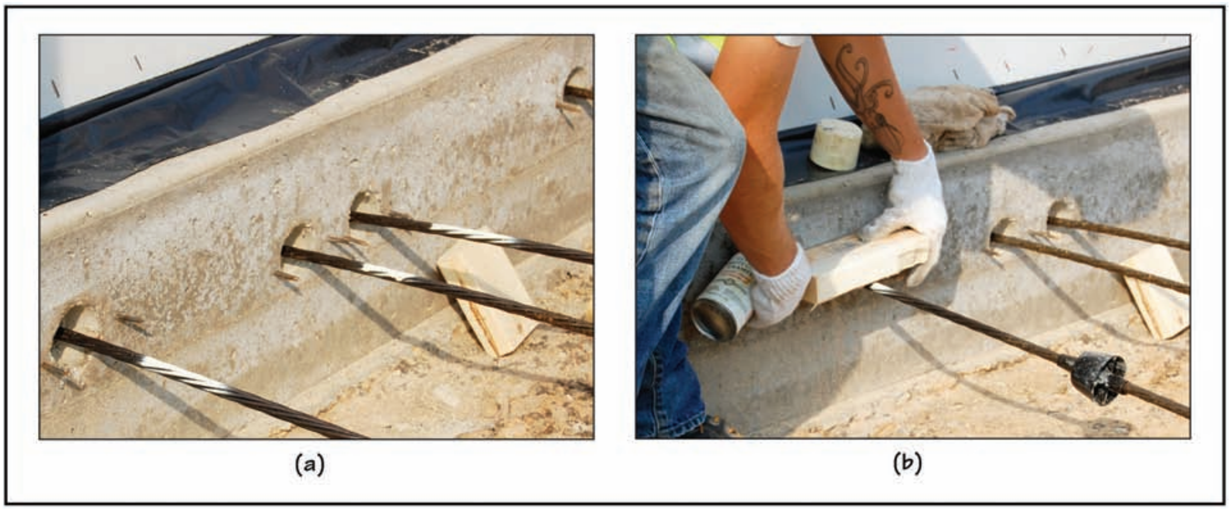


FIGURE 22.48 **(a)** Before starting the prestressing operation, as shown in Figure 22.47, the strands are paint marked a constant distance from the concrete member. The marks help in determining the elongation of strands after prestressing. **(b)** Holding a paint can, a worker marks the strand using a 2 × 4 wood member to provide a constant distance from the edge of the concrete member.

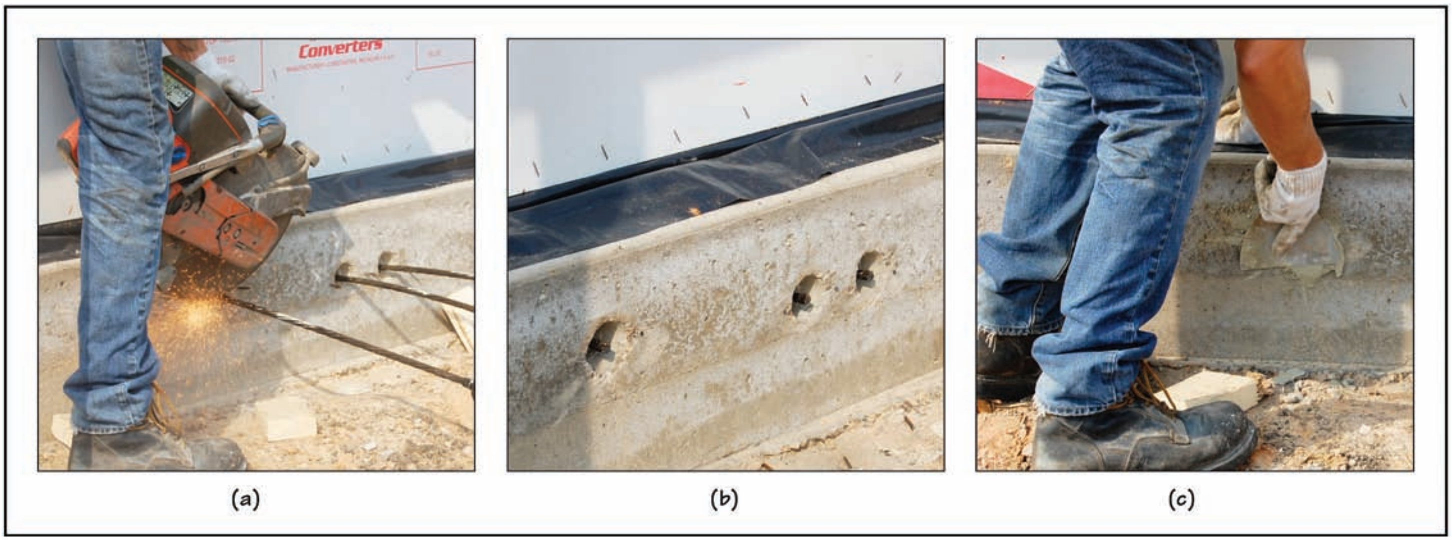


FIGURE 22.49 **(a)** and **(b)** After the prestressing operation, the strands are saw-cut. **(c)** After the strands have been cut, the pocket in the concrete member is grout filled and troweled smooth.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

26. The most important reason for providing ties in a concrete column is to
- **a.** prevent the buckling of longitudinal column bars.
- **b.** increase the compressive strength of a column.
- **c.** increase the shear strength of a column.
- **d.** allow the formwork to be tied to the longitudinal bars in the column.
- **e.** Ties are generally not provided in a concrete column.

27. The most important reason for providing ties in a concrete wall is to
- **a.** prevent the buckling of longitudinal bars in the wall.
- **b.** increase the compressive strength of the wall.
- **c.** increase the shear strength of the wall.
- **d.** allow the formwork to be tied to the longitudinal bars in the wall.
- **e.** Ties are generally not provided in a concrete wall.

28. Formwork for a concrete wall generally consists of
- **a.** plywood, form ties, and walers fastened together with duplex nails.
- **b.** plywood, form ties, walers, and stiffbacks fastened together with duplex nails.
- **c.** plywood, form ties, walers, and stiffbacks fastened together with clamps.
- **d.** plywood and stiffbacks fastened together with clamps.

29. A vapor retarder is required under
- **a.** all concrete slabs-on-ground.
- **b.** all exterior concrete slabs-on-ground.
- **c.** all interior concrete slabs-on-ground.
- **d.** under some interior concrete slabs-on-ground.

30. The strength of concrete in a residential concrete slab-on-ground is generally
- **a.** 1,000 psi.
- **b.** 2,000 psi.
- **c.** 3,000 psi.
- **d.** 4,000 psi.
- **e.** 5,000 psi.

31. A construction joint in a concrete slab-on-ground is required if the concrete in the slab cannot be placed in one continuous operation.
- **a.** True
- **b.** False

32. The tendons used for prestressing a PT concrete slab-on-ground generally consist of
- **a.** a single $\frac{1}{2}$-in.-diameter, nine-wire strand.
- **b.** a single $\frac{1}{2}$-in.-diameter, seven-wire strand.
- **c.** two-strand tendons, each strand made of seven wires.
- **d.** three-strand tendons, each strand made of seven wires.
- **e.** none of the above.

33. In a PT concrete slab-on-ground, the tendons are stressed from the
- **a.** dead ends.
- **b.** live ends.
- **c.** upper ends.
- **d.** lower ends.
- **e.** any one of the above.

34. Pocket formers in a PT concrete slab-on-ground are used at
- **a.** dead ends.
- **b.** live ends.
- **c.** upper ends.
- **d.** lower ends.
- **e.** any one of the above.

35. A PT concrete slab-on-ground may either be a ribbed slab or a constant-thickness slab.
- **a.** True
- **b.** False

REVIEW QUESTIONS

1. Describe the differences between pretensioning and posttensioning of concrete. Is there any difference in the type of steel used in each case?
2. Describe the difference between (a) reinforcing steel and prestressing steel, (b) formwork and shores, (c) formwork and flying forms, and (d) shoring and reshoring.
3. Concrete reinforcing bars come in limited lengths. Explain how we ensure their continuity in a long structural element, such as a column in a high-rise building or a long, continuous beam.
4. Explain what concrete cover is and the functions it serves.
5. What is the function of stirrups? Sketch commonly used open-loop and closed-loop stirrups.
6. Using sketches and notes, explain the typical layout of reinforcement in a simply supported, reinforced-concrete beam.
7. List various types of reinforced-concrete slabs as described in this text, and the essential differences between them.
8. Sketch a typical (a) control joint in a slab-on-ground, (b) construction joint in a slab-on-ground, (c) isolation joint in a slab-on-ground, and (d) prestressing strand.
9. Sketch in section a typical ribbed concrete slab-on-ground.

CHAPTER 23

Concrete Construction–II (Site-Cast and Precast Concrete Framing Systems)

CHAPTER OUTLINE

23.1 Types of Elevated Concrete Floor Systems

23.2 Beam-Supported Concrete Floors

23.3 Beamless Concrete Floors

23.4 Posttensioned Elevated Concrete Floors

23.5 Introduction to Precast Concrete

23.6 Structural Precast Concrete Members

23.7 Total Precast Concrete Construction

23.8 Fire Resistance of Concrete Members

This chapter is a continuation of Chapter 22. It begins with a discussion of commonly used types of elevated site-cast concrete slabs. (Slabs-on-ground were covered in Chapter 22.)

This is followed by coverage of precast, prestressed concrete elements such as hollow-core slabs, solid planks, double-tee units, and inverted-tee beams. Construction systems related to these elements are also discussed.

23.1 TYPES OF ELEVATED CONCRETE FLOOR SYSTEMS

Site-cast reinforced-concrete framing systems consist of horizontal elements (elevated floor/roof slabs and beams) and vertical elements (columns and walls). Approximately 80% to 95% of the cost of materials and formwork of a concrete structural frame is in the horizontal framing elements of the frame. Consequently, the choice of the elevated floor system is the most important item in a concrete structure.

Elevated concrete floor systems can be classified as: (a) beam-supported floors and (b) beamless floors. They are further divided into several types, Figure 23.1.

23.2 BEAM-SUPPORTED CONCRETE FLOORS

A reinforced-concrete floor slab with beams on all four sides can either be a *one-way slab* or a *two-way slab*. They are also called *one-way solid slabs* or *two-way solid slabs* to distinguish them from one-way joist slabs or two-way joist slabs, which are not completely solid.

The transfer of loads from a solid slab to the four supporting beams is represented approximately by 45° lines originating from the slab corners, Figure 23.2(a). If the slab panel is a square, each supporting beam receives the same amount of load, Figure 23.2(b). If the slab panel is rectangular, one pair of beams carries a greater load than the other pair.

NOTE

Preliminary Thickness of One-Way and Two-Way Slabs

Estimate the thickness of a one-way slab by dividing the slab span by 24. Thus, if the slab span is 12 ft, use a slab approximately 6 in. thick.

Two-way slab thickness is span/36. Use the longer of the two spans. Thus, if a slab panel measures 16 ft × 21 ft, the slab thickness is approximately $\frac{21}{36} = \frac{7}{12}$ ft, or a 7-in.-thick slab.

Also see Appendix B, and consult a structural engineer for exact sizes.

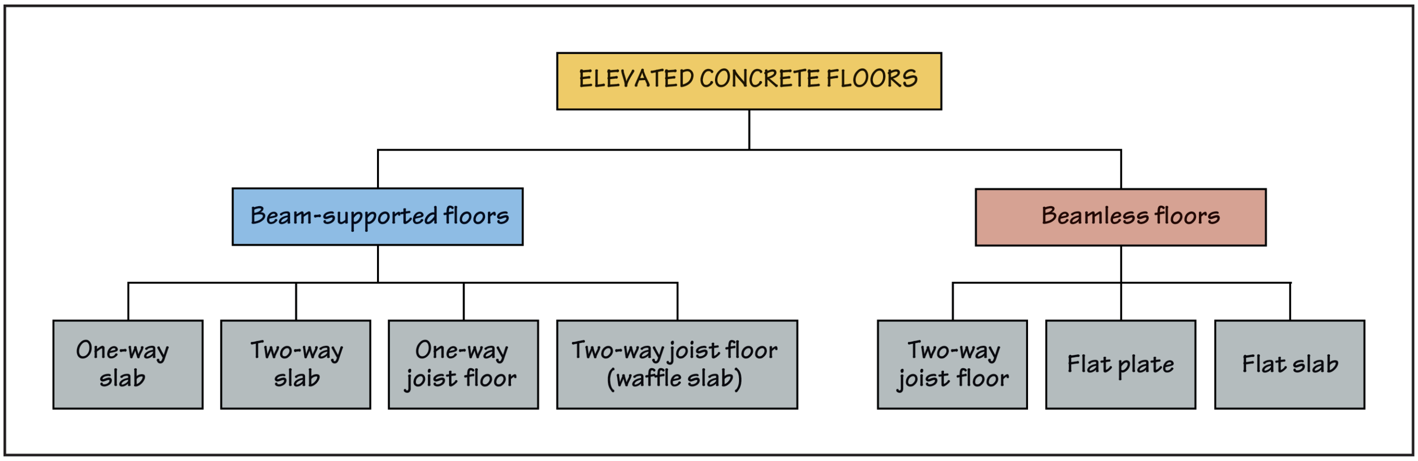

ELEVATED CONCRETE FLOORS
Beam-supported floors
Beamless floors
One-way slab
Two-way slab
One-way joist floor
Two-way joist floor (waffle slab)
Two-way joist floor
Flat plate
Flat slab

FIGURE 23.1 Types of elevated concrete floors.

ONE-WAY SOLID SLAB

If the ratio of the long dimension to the short dimension of a four-side-supported slab panel is greater than or equal to 2.0, most of the load on the slab is transferred to the long pair of beams, that is, the load path is along the short dimension of the slab panel, Figure 23.2(c). The load path along the long dimension of the slab is negligible.

Because the load is effectively transferred along one direction in Figure 23.2(c), the slab behaves as a one-way slab. The reinforcement in a one-way slab is placed along the short direction, referred to as the *primary reinforcement* to distinguish it from the nominal reinforcement placed along the perpendicular direction, called the *secondary reinforcement*. The purpose of secondary reinforcement is to resist stresses caused by concrete shrinkage and thermal expansion and contraction of the slab.

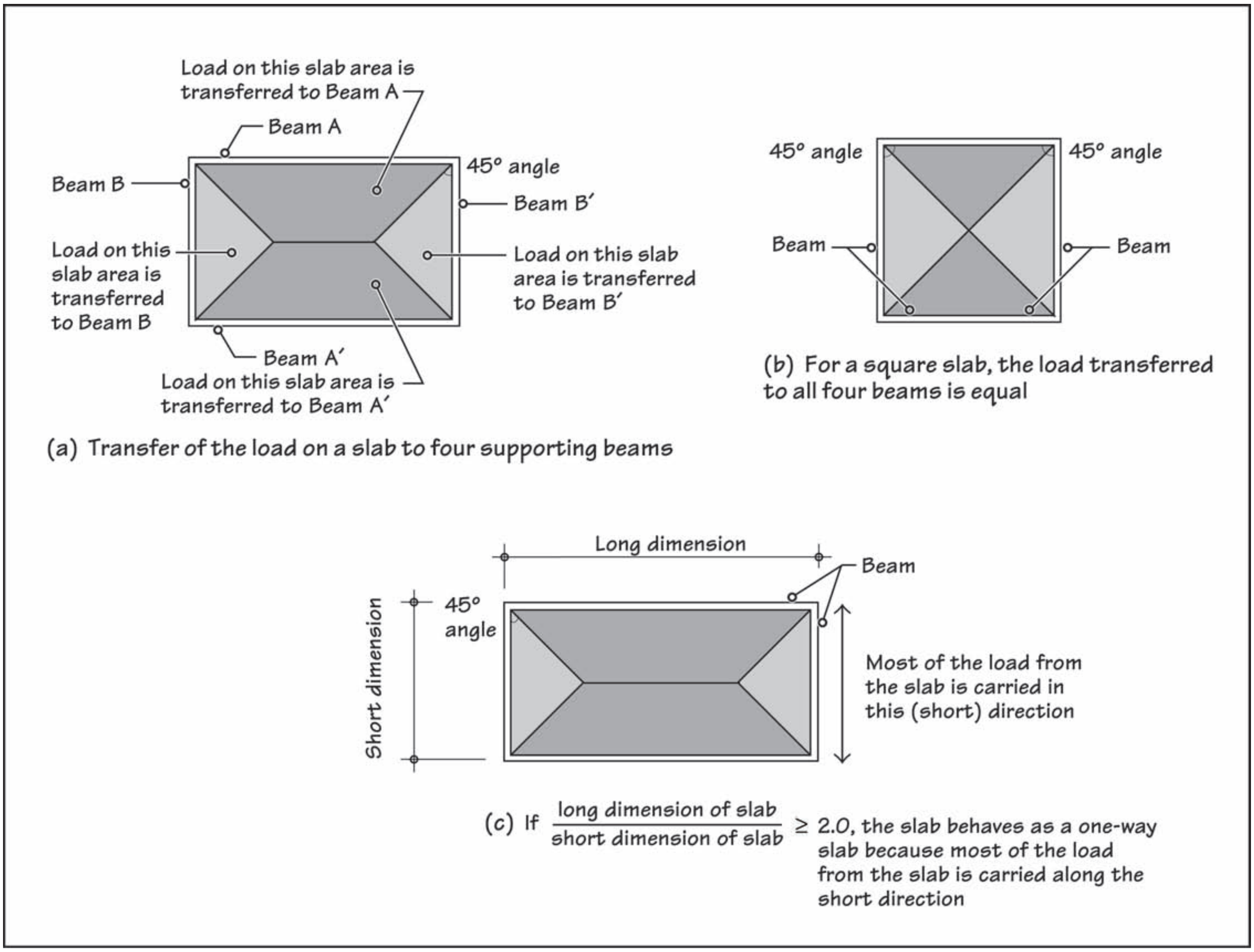

Load on this slab area is transferred to Beam A
Beam A
45° angle
Beam B
Beam B′
Load on this slab area is transferred to Beam B
Load on this slab area is transferred to Beam B′
Beam A′
Load on this slab area is transferred to Beam A′
(a) Transfer of the load on a slab to four supporting beams
45° angle
45° angle
Beam
Beam
(b) For a square slab, the load transferred to all four beams is equal
Long dimension
Beam
45° angle
Short dimension
Most of the load from the slab is carried in this (short) direction
(c) If long dimension of slab / short dimension of slab ≥ 2.0, the slab behaves as a one-way slab because most of the load from the slab is carried along the short direction

FIGURE 23.2 Distinction between one-way and two-way concrete slabs supported by beams on all four sides.

Two-Way Solid Slab

If the ratio of the long to the short dimension of a four-side-supported slab panel is less than 2.0, the slab is considered to behave as a *two-way slab*. However, real two-way slab behavior occurs when the ratio of the two dimensions is as close to 1.0 as possible (between 1.0 and 1.25). In a two-way slab, both directions participate in carrying the load. Reinforcement is, therefore, provided in both directions as primary reinforcement. Although not common, both one-way and two-way slabs may occur in the same floor, Figure 23.3.

Beam-and-Girder Floors

One-way and two-way solid slabs become increasingly thick and hence uneconomical as their span increases. Generally, the use of a slab thicker than 8 in. is discouraged because it creates a large dead load on the floor. For a one-way slab, an 8-in. slab thickness is reached with a span of approximately 16 ft. For a square two-way slab, a span of approximately 24 ft requires an 8-in.-thick slab.

Because 16-ft and 24-ft dimensions are relatively small for column spacing, one-way and two-way slabs are generally used in a *beam-and-girder floor*, Figure 23.4(a), or in a *two-way beam-and-girder floor*, Figure 23.4(b).

Band Beam Floor

A concrete floor that cannot be constructed with a flat form deck becomes uneconomical. Therefore, the floor systems shown in Figure 23.4 are relatively uncommon because of the complexity of the formwork resulting from deep beams around slab panels.

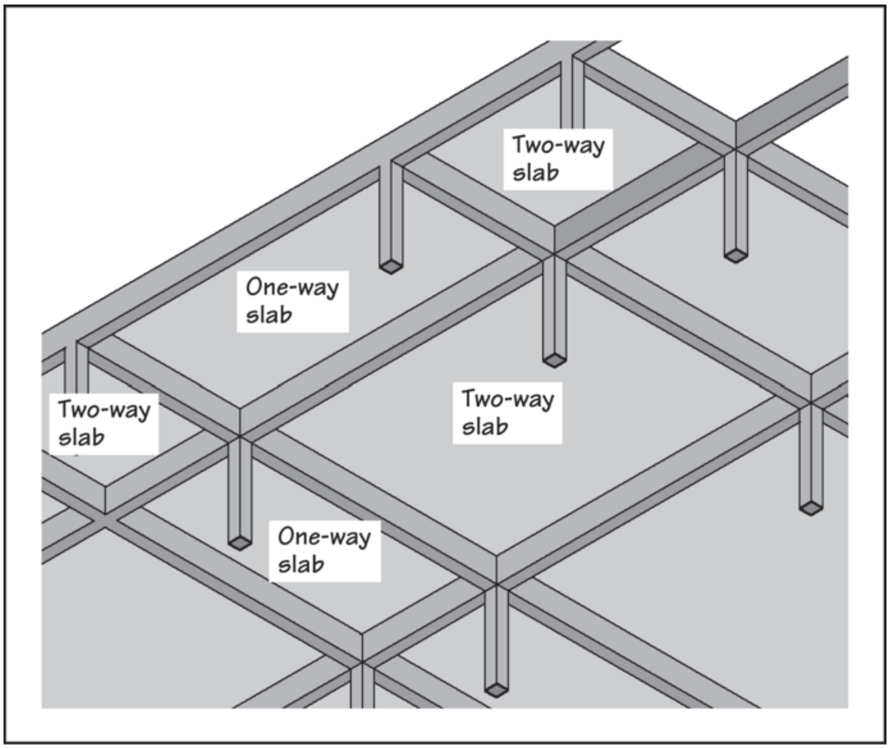
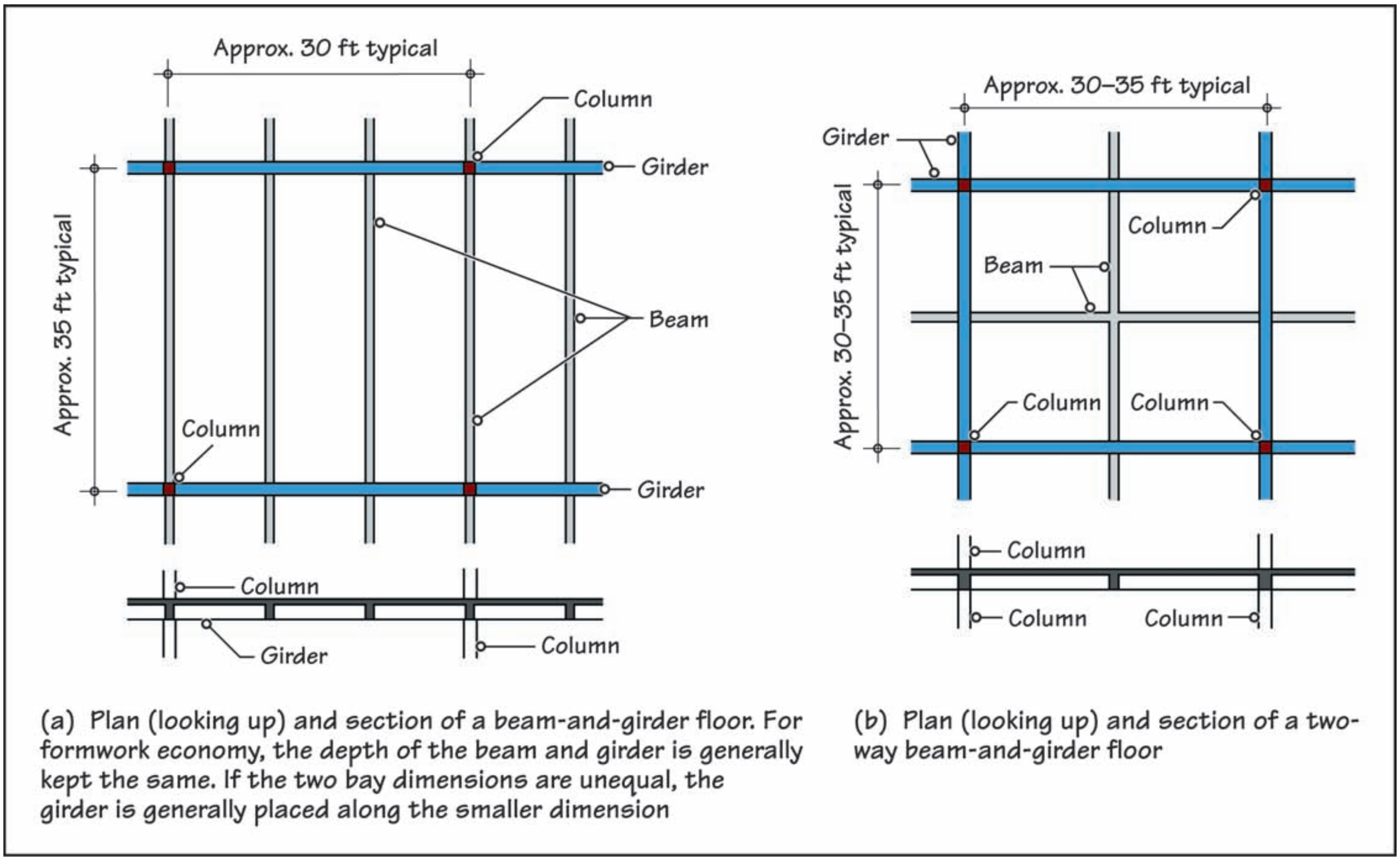

Two-way
slab
One-way
slab
Two-way
slab
Two-way
slab
One-way
slab

FIGURE 23.3 Although not common, one-way and two-way slabs can occur in the same floor.


Approx. 30 ft typical
Column
Girder
Beam
Approx. 35 ft typical
Column
Girder
Column
Girder
Column
Approx. 30–35 ft typical
Girder
Column
Beam
Approx. 30–35 ft typical
Column
Column
Column
Column
Column

(a) Plan (looking up) and section of a beam-and-girder floor. For formwork economy, the depth of the beam and girder is generally kept the same. If the two bay dimensions are unequal, the girder is generally placed along the smaller dimension

(b) Plan (looking up) and section of a two-way beam-and-girder floor

FIGURE 23.4 Plan and section through beam-and-girder floors.

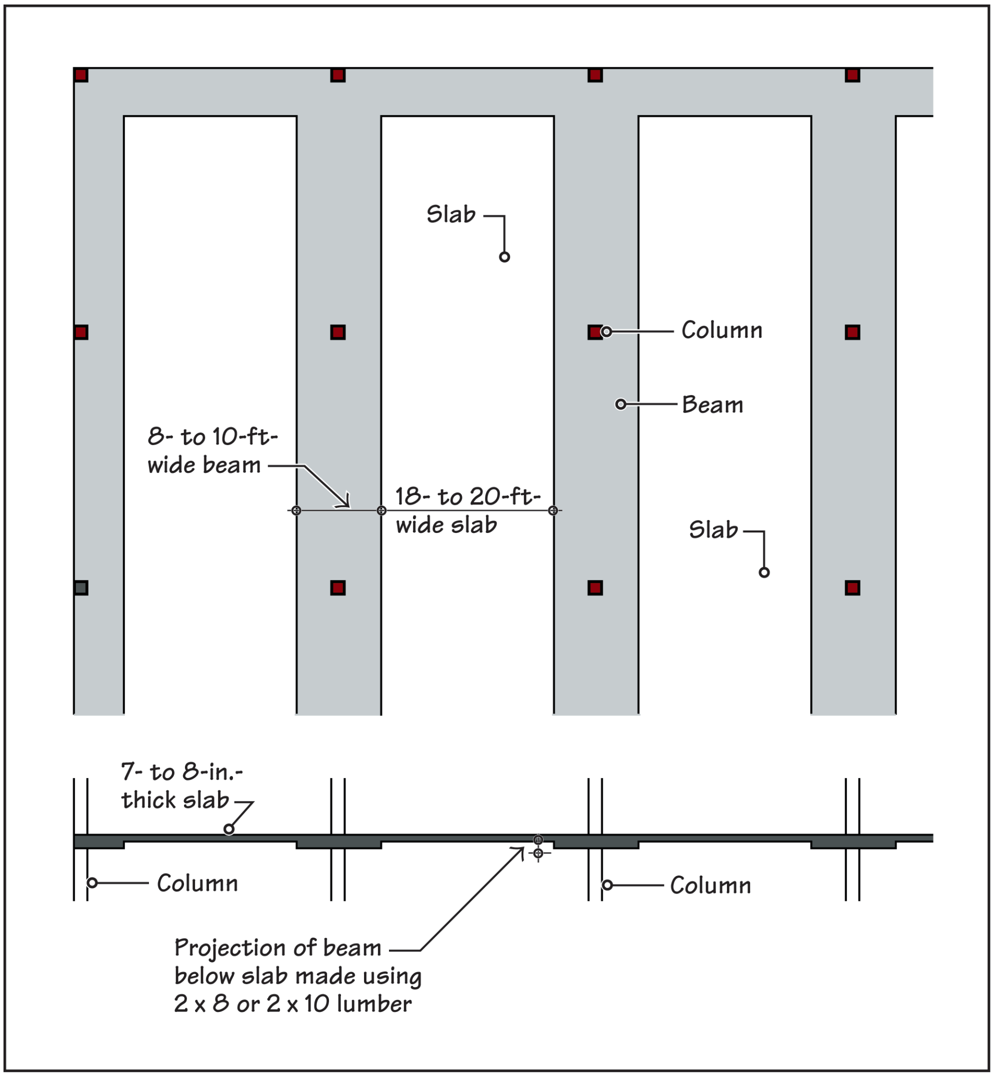


FIGURE 23.5 Plan (looking up) and section through a typical banded slab, which yields a more economical formwork than the beam-and-girder system in Figure 23.4. The projection of the beam below the bottom of the slab is generally obtained by using dimension lumber, such as 2 × 8, 2 × 10, and so on. This illustration also shows typical spans and member thickness (also see Appendix B).

A one-way slab floor with wide and shallow, continuous beams, referred to as *band beams* (in contrast with the conventional *narrow beams*), gives more economical formwork, Figure 23.5. Because the beams are wide, the slab span is reduced, reducing the slab thickness. Additionally, because the beams are shallow, the floor-to-floor height is smaller, reducing the height of columns, interior partitions, and exterior cladding. A smaller floor-to-floor height also reduces the overall height of the building, which reduces the magnitude of lateral loads on the building.

ONE-WAY JOIST FLOOR

A concrete floor that results from extremely economical formwork consists of closely spaced, narrow ribs in one direction supported on beams in the other direction, Figure 23.6. Because the ribs are narrow and closely spaced, the floor resembles a wood joist floor. It is, therefore, called a *joist floor* or a *ribbed floor*, but it is more commonly known as a *one-way joist floor* to distinguish it from the *two-way joist floor* described later.

A one-way joist floor is constructed with U-shaped pans as formwork placed over a flat-form deck. The gap between the pans represents the width of the joists, which can be adjusted by placing the pans closer together or farther apart, Figure 23.7. The pans are generally made of steel or glass fiber–reinforced plastic (GFRP) and can be used repeatedly.

The vertical section through a pan tapers downward for easy stripping and has supporting lips at both ends. Pan widths and heights have been standardized to give two categories of one-way joist floors:

- Standard-module one-way joist floor
- Wide-module one-way joist floor

STANDARD-MODULE ONE-WAY JOIST FLOOR

Standard-module pans are 20 in. and 30 in. wide, Figure 23.8. These dimensions have been standardized so that, with 4-in.- and 6-in.-wide joists, the center-to-center spacings between

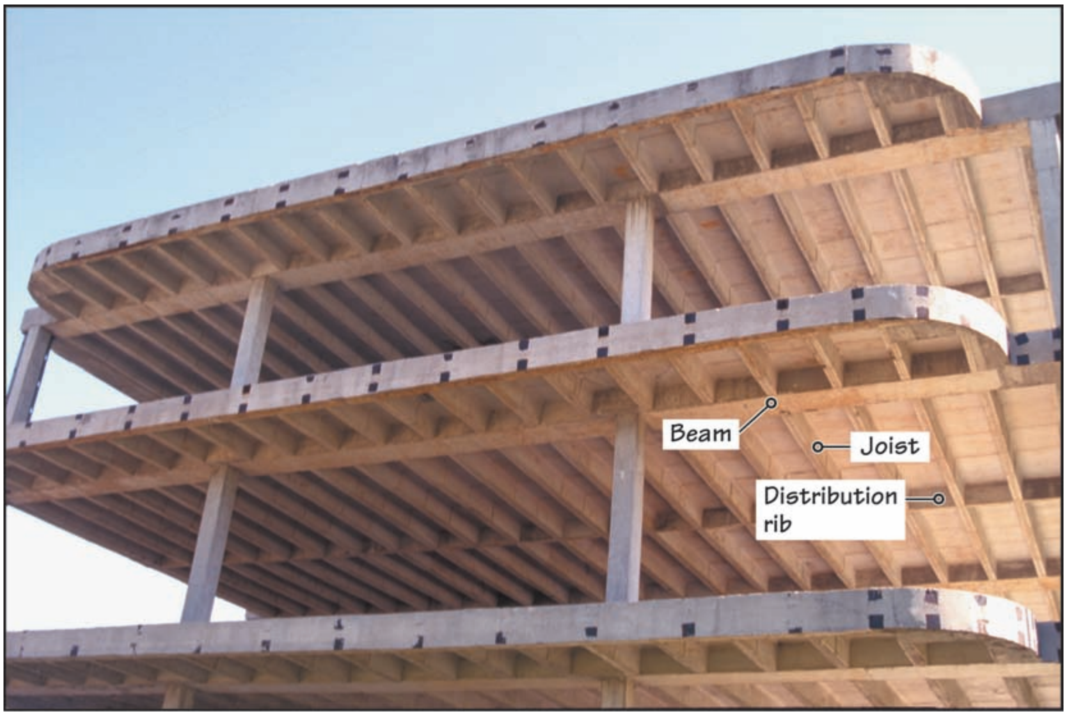


FIGURE 23.6 A one-way joist floor. Observe that the bottom of the beams and joists is at the same level to allow the entire slab to be formed on a flat-form deck.

joists are 2 ft and 3 ft, respectively. A slab thickness of $3\frac{1}{2}$ in. is often used (to provide a 1-h fire-rated floor), although structural considerations require a minimum thickness of only 2 in. with 20-in. pans and $2\frac{1}{2}$ in. with 30-in. pans. The slab is designed as a one-way slab resting on the joists, which, in turn, are designed as beams.

Pans of various depths are available to create joists of various depths to suit different joist spans. Because the load on each joist is small, reinforcement requirements are also small. No stirrups are generally used in joists, thus requiring the concrete to resist the entire shear. The increase in shear near-joist supports is resisted, if needed, by increasing the joist width, Figure 23.9. Special pans with closed ends on one side are available to produce the widening of joists.

A 4- to 5-in.-wide load-distribution rib is often provided in the center of joists.

WIDE-MODULE ONE-WAY JOIST FLOOR

Wide-module pans are available in 53-in. and 66-in. widths, Figure 23.10. They are generally used with 5-ft and 6-ft center-to-center joist spacings, giving joist widths of 7 in. and 6 in., respectively. However, almost any joist width can be created to suit the load and span conditions. Joist widths of 8 in. and 9 in. are also common.

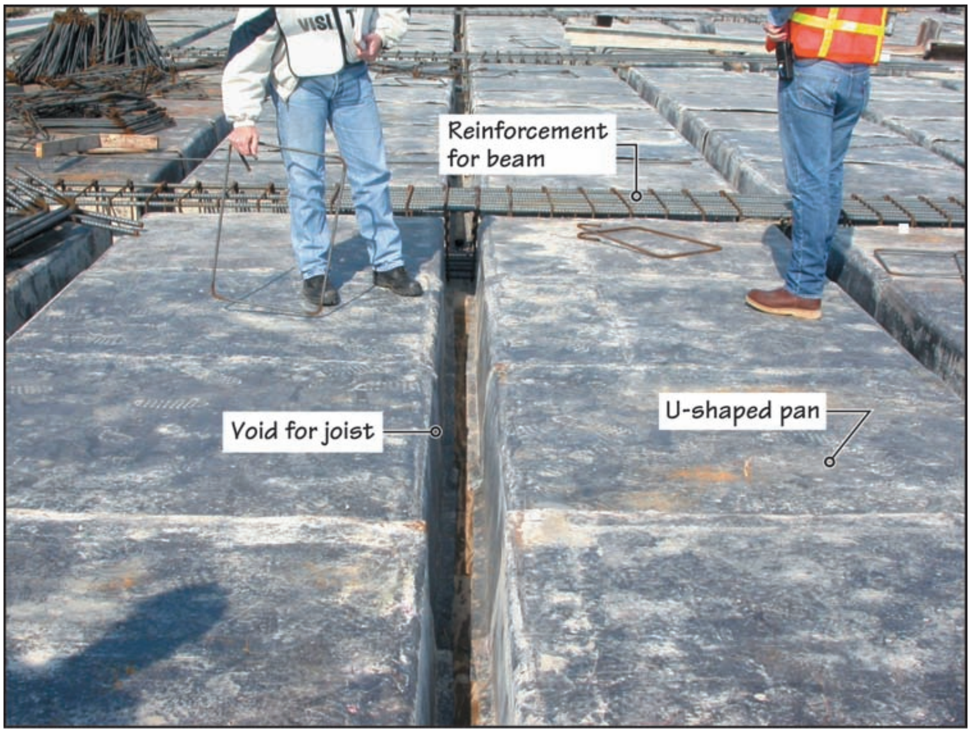


FIGURE 23.7 Formwork for a one-way joist floor showing U-shaped pans. The space between the pans represents the width of the joists. Notice that reinforcement for beams has already been laid. Reinforcement for joists and the slab is yet to be completed (also see Figure 23.11).

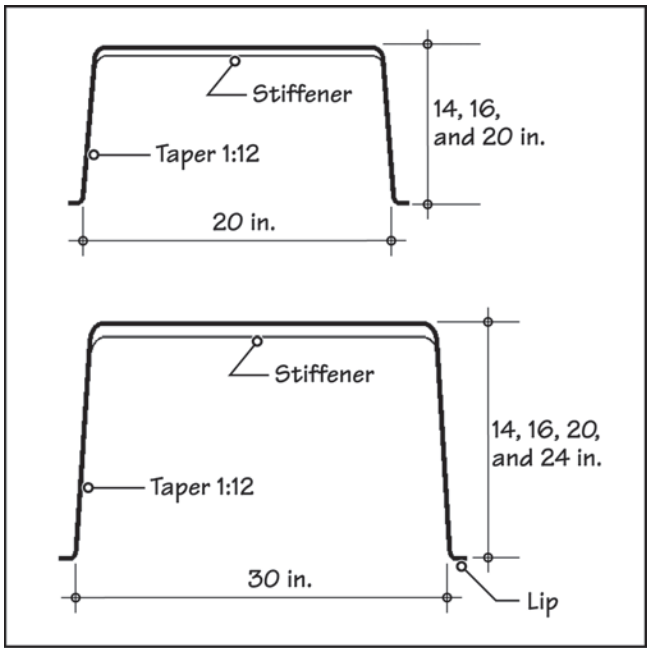

Stiffener
Taper 1:12
14, 16,
and 20 in.
20 in.
Stiffener
Taper 1:12
14, 16, 20,
and 24 in.
30 in.
Lip

FIGURE 23.8 U-shaped standard-module pans (consult the manufacturer for available sizes). Note that the pans have open ends on both sides, except the pans used adjacent to beam or the distribution rib, which have closed ends (see Figure 23.9).

NOTE

Preliminary Depth of a One-Way Joist Floor

Estimate the depth of a one-way joist floor by dividing the joist span by 18. Thus, if the span of joists is 36 ft, use 24-in.-deep joists, which includes the thickness of the slab. Using a $4\frac{1}{2}$-in.-thick slab and 20-in.-deep pans for a wide-module floor gives a floor depth of $24\frac{1}{2}$ in.

Where the spacing of columns in either direction is unequal, the supporting beams should preferably be oriented along the shorter direction and the joists in the longer direction.

Also see Appendix B, and consult a structural engineer for exact sizes.

Because a wide-module floor has a larger spacing between joists, the slab thickness required is also larger. Therefore, a wide-module floor is generally used where a minimum fire rating of 1 h (required slab thickness $= 3\frac{1}{2}$ in.) or 2 h (required slab thickness $= 4\frac{1}{2}$ in.) is needed.

Figure 23.11 shows the overall view of a wide-module one-way joist floor with rebars in place. As shown in this figure, the joists in a wide-module floor are generally designed with shear reinforcement (stirrups). Therefore, the widening of joist ends at beams is unnecessary. Special end caps are available to close the open ends of pans near the beams, Figure 23.12.

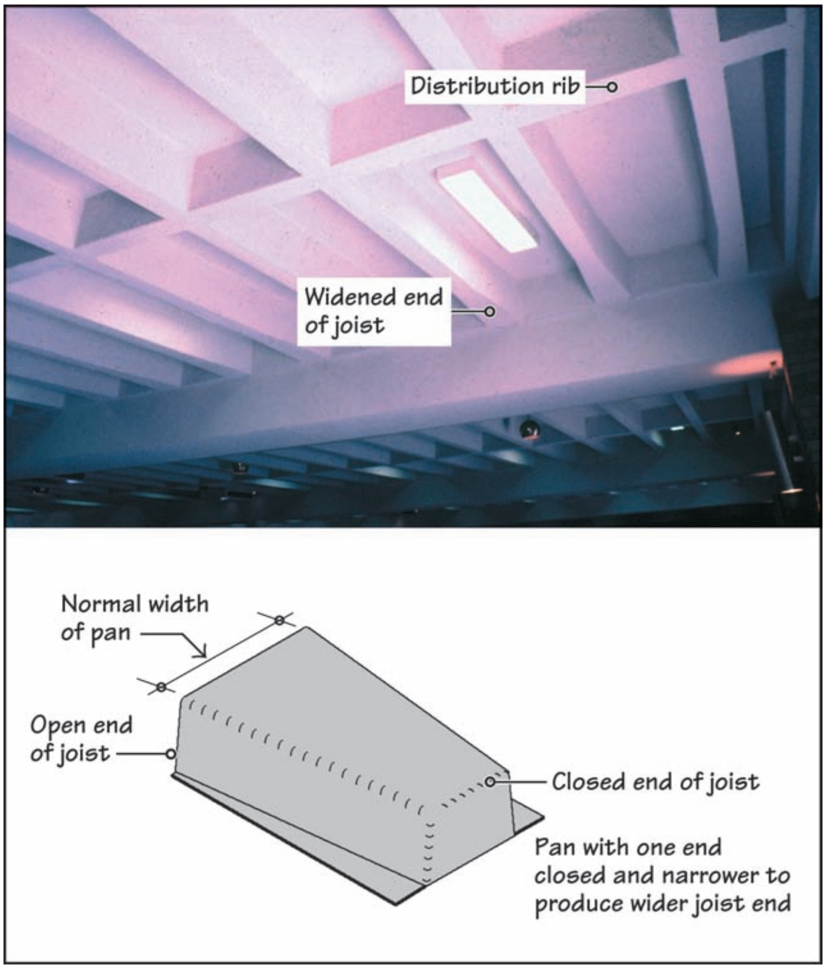

Distribution rib
Widened end of joist
Normal width of pan
Open end of joist
Closed end of joist
Pan with one end closed and narrower to produce wider joist end

FIGURE 23.9 A one-way joist floor with standard pans. Observe that the joist width has been increased near the beams to accommodate greater shear in the joists at that location. The beams in this slab are deeper than the joists. This is unusual because it increases the cost of formwork compared with the slab with the same depth of joists and beams, as shown in Figure 23.6. A distribution rib has been provided in the center of the slab.

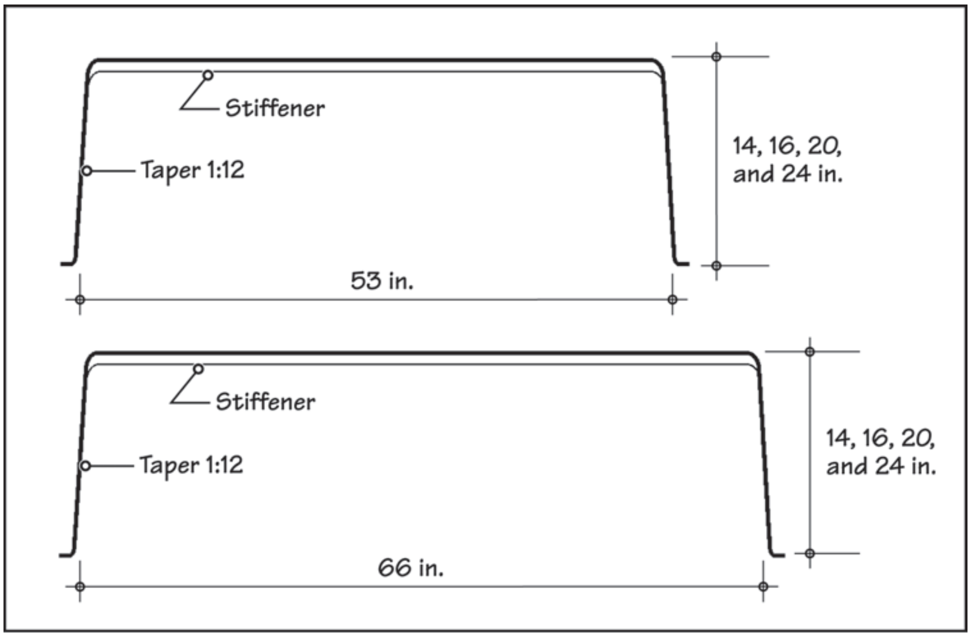

Stiffener
Taper 1:12
14, 16, 20, and 24 in.
53 in.
Stiffener
Taper 1:12
14, 16, 20, and 24 in.
66 in.

FIGURE 23.10 Wide-module pan dimensions. Consult manufacturers for available sizes.

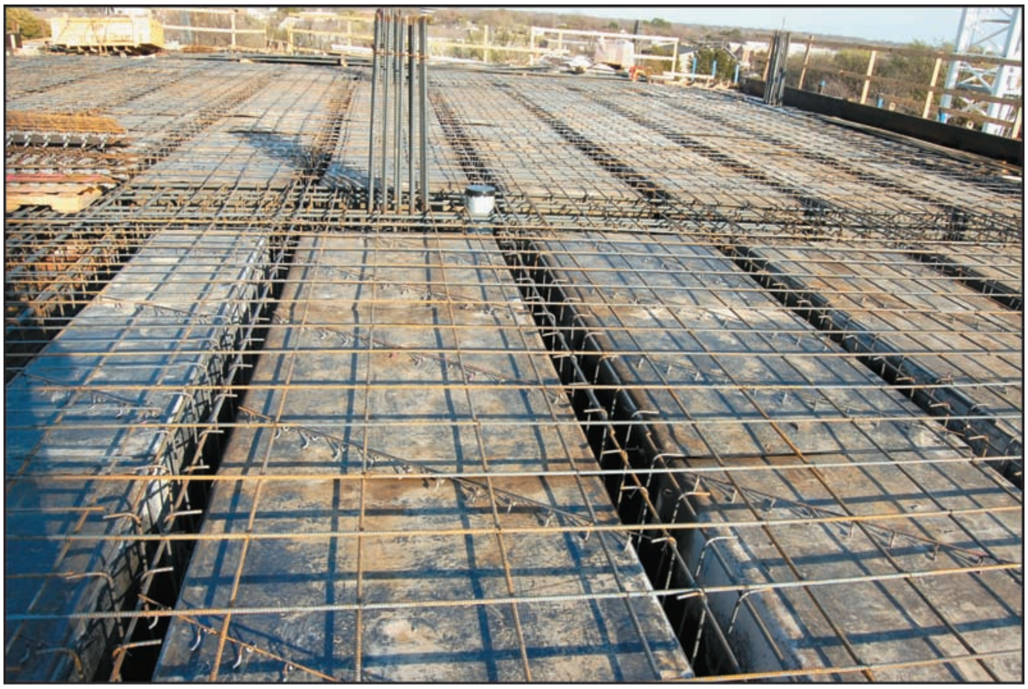


FIGURE 23.11 An overall view of a wide-module one-way joist floor formwork with rebars in place—ready to receive concrete. Observe the use of shear reinforcement (stirrups) in the joists.

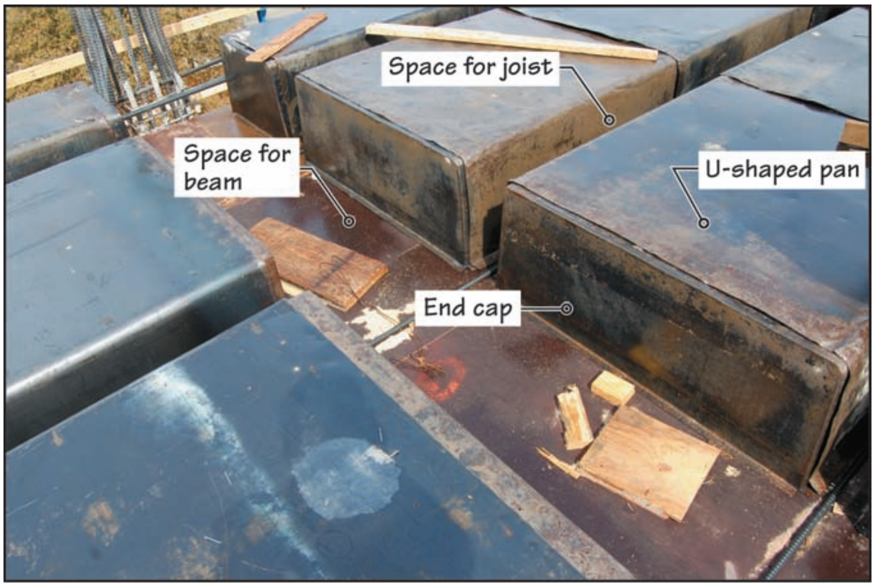

Space for joist
Space for beam
U-shaped pan
End cap

FIGURE 23.12 Wide-module pans and end caps. Because both ends of the pans are open, end caps are needed to close the gap to form a void for the beam.

NOTE

Preliminary Depth of a Two-Way Joist Floor

Estimate the depth of a waffle slab by dividing the longer span by 22. Thus, if the two-way joist floor span is 44 ft, use a 2-ft (i.e., 24-in.)-deep floor that includes the thickness of the slab. Using a $4\frac{1}{2}$-in.-thick slab for a 2-h rated floor and 20-in.-deep domes gives a floor depth of $24\frac{1}{2}$ in.

Also see Appendix B, and consult a structural engineer for exact sizes.

TWO-WAY JOIST FLOOR (WAFFLE SLAB)

A two-way joist floor, also called a *waffle slab*, consists of joists in both directions, Figure 23.13. For the same depth of joists, a waffle slab yields a stiffer floor than a one-way joist floor. It is, therefore, used where the column-to-column spacing lies between 35 ft and 50 ft. A waffle slab is best suited for square or almost square column-to-column bays. When left exposed to the floor below, the waffle slab provides a highly articulated ceiling.

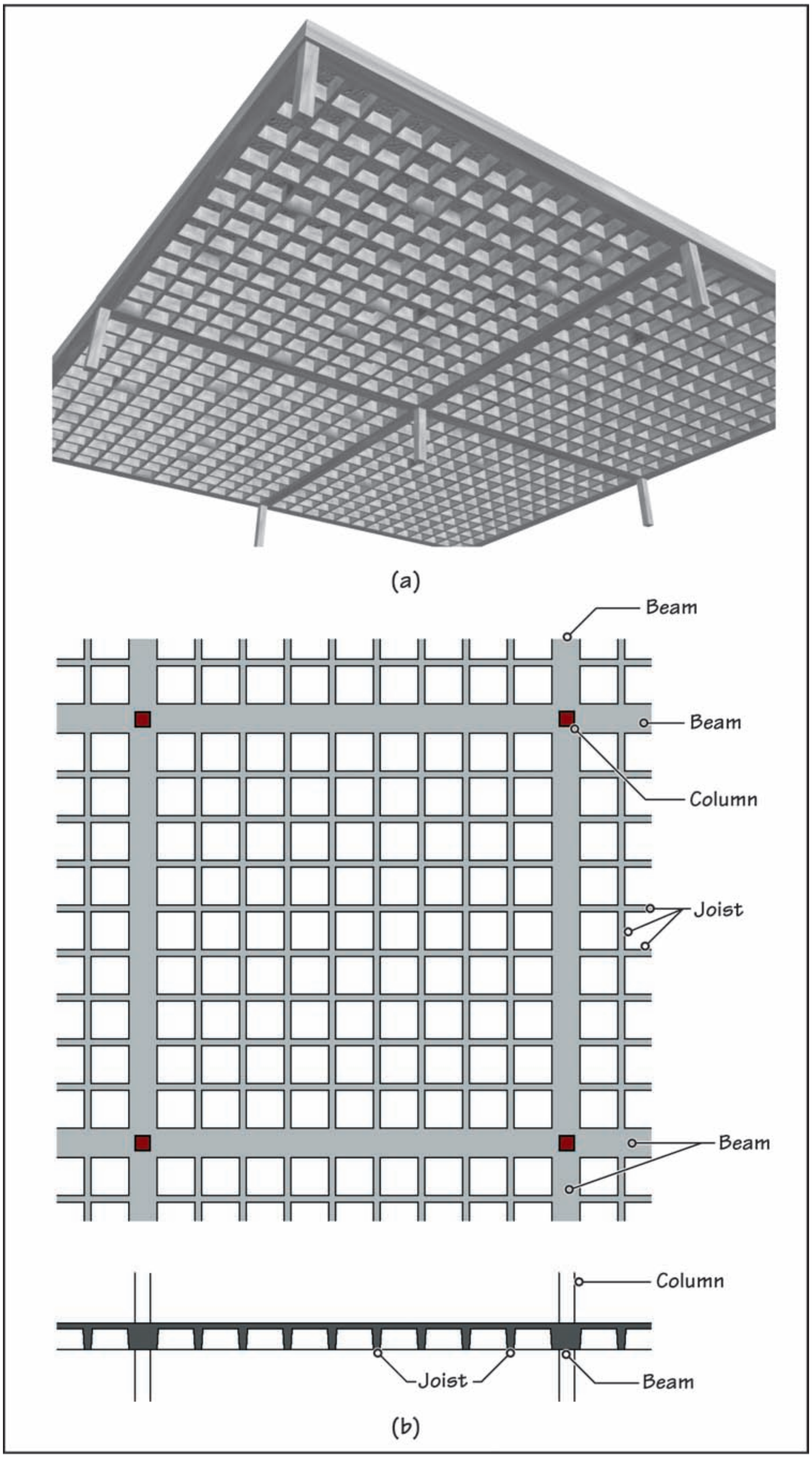


FIGURE 23.13 Two-way joist floor (waffle slab) supported on beams on all sides. **(a)** Isometric from below. **(b)** Plan (looking up) and section through the slab. Note that a waffle slab can also be constructed without beams, as shown in Figure 23.15.

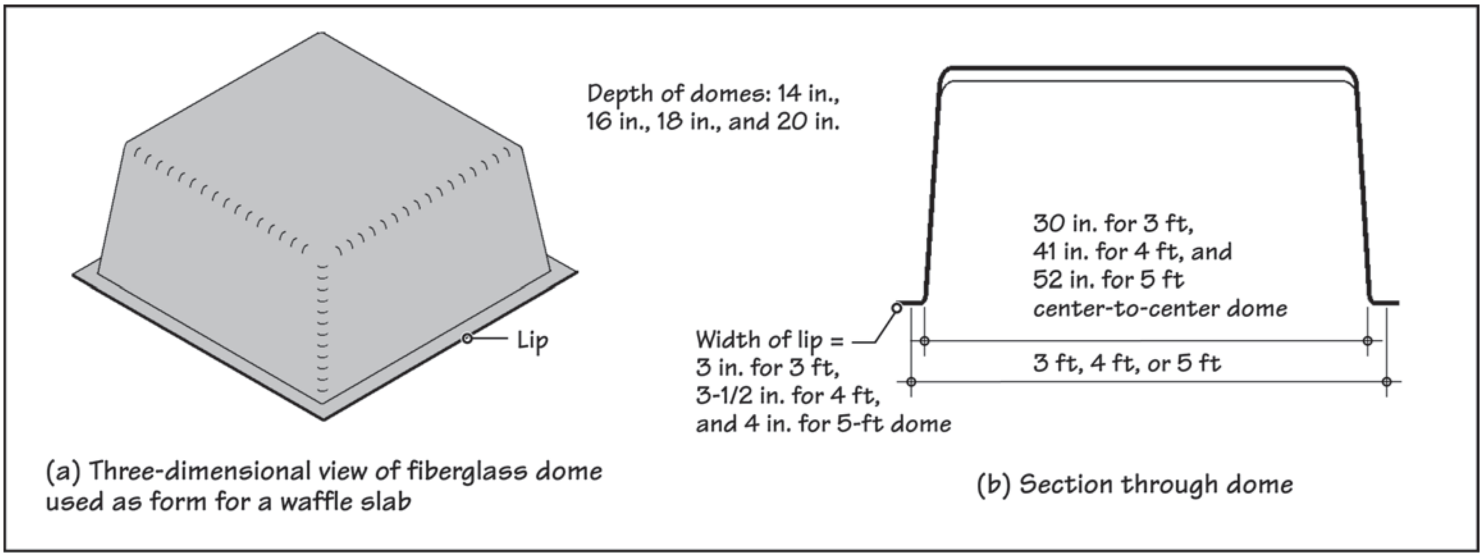

Depth of domes: 14 in., 16 in., 18 in., and 20 in.
Lip
30 in. for 3 ft, 41 in. for 4 ft, and 52 in. for 5 ft center-to-center dome
Width of lip = 3 in. for 3 ft, 3-1/2 in. for 4 ft, and 4 in. for 5-ft dome
3 ft, 4 ft, or 5 ft
(a) Three-dimensional view of fiberglass dome used as form for a waffle slab
(b) Section through dome

FIGURE 23.14 Standard GFRP dome sizes for a waffle slab. Consult manufacturers for available sizes.

The formwork for the slab consists of glass fiber–reinforced plastic domes placed on a flat form deck with the lips butting each other, Figure 23.14. Like the pans, the domes can withstand repeated use. Dome dimensions have been standardized to produce 3-ft, 4-ft, and 5-ft center-to-center distances between domes in a variety of depths. The domes have a wide supporting lip on all sides and are laid on a flat-form deck.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. A reinforced concrete, four-side-supported slab panel is
- **a.** a one-way slab.
- **b.** a two-way slab.
- **c.** a four-way slab.
- **d.** (a) or (b).
- **e.** (b) or (c).

2. A reinforced-concrete, four-side-supported slab panel measuring 15 ft × 22 ft is
- **a.** a one-way slab.
- **b.** a two-way slab.
- **c.** a four-way slab.
- **d.** (a) or (b).
- **e.** none of the above.

3. A reinforced-concrete, four-side-supported slab panel measuring 15 ft × 32 ft is
- **a.** a one-way slab.
- **b.** a two-way slab.
- **c.** a four-way slab.
- **d.** (a) or (b).
- **e.** none of the above.

4. In a band beam reinforced-concrete floor, the beams are
- **a.** narrow and deep.
- **b.** wide and shallow.
- **c.** located at a spacing of 8 ft to 10 ft on center.
- **d.** unnecessary.

5. A band beam floor is generally more economical than a beam-and-girder floor because
- **a.** it requires a smaller quantity of concrete.
- **b.** it requires a smaller quantity of reinforcement.
- **c.** its formwork is more economical.
- **d.** none of the above.

6. A standard-module one-way joist floor is constructed using pans that are
- **a.** 20 in. wide.
- **b.** 30 in. wide.
- **c.** 40 in. wide.
- **d.** (a) or (b).
- **e.** (b) or (c).

7. Based on structural considerations only, the thickness of the slab in a standard-module one-way joist floor need not exceed
- **a.** 2 in. to $2\frac{1}{2}$ in.
- **b.** 3 in. to $3\frac{1}{2}$ in.
- **c.** 4 in. to 5 in.
- **d.** 5 in. to 6 in.

8. Pans used as formwork for one-way joist floors have a
- **a.** U-shaped profile.
- **b.** Z-shaped profile.
- **c.** dome profile.
- **d.** any one of the above.
- **e.** none of the above.

9. A wide-module one-way joist floor is constructed using pans that are
- **a.** 66 in. wide.
- **b.** 60 in. wide.
- **c.** 53 in. wide.
- **d.** (a) or (b).
- **e.** (a) or (c).

10. In a one-way joist floor, the supporting beams run in one direction and the joists run in the other direction. If the spans in the two directions are unequal, the beams should preferably span along the
- **a.** shorter direction.
- **b.** longer direction.

11. The formwork used for a waffle slab has a
- **a.** U-shaped profile.
- **b.** Z-shaped profile.
- **c.** dome profile.
- **d.** any one of the above.
- **e.** none of the above.

12. Using standard formwork components for a waffle slab, the center-to-center distance between waffles (voids) is
- **a.** 3 ft, 4 ft, or 5 ft.
- **b.** 2 ft, 4 ft, or 6 ft.
- **c.** 4 ft, 5 ft, or 6 ft.
- **d.** 5 ft, 6 ft, or 7 ft.
- **e.** none of the above.

23.3 BEAMLESS CONCRETE FLOORS

A waffle slab is more commonly constructed as a beamless slab, Figure 23.15. In a beamless waffle slab, a few domes on all sides of a column are omitted so that the thickness of the slab at the columns is the same as the depth of the joists. The thickening of the slab at the columns provides shear resistance (against the slab punching through the columns).

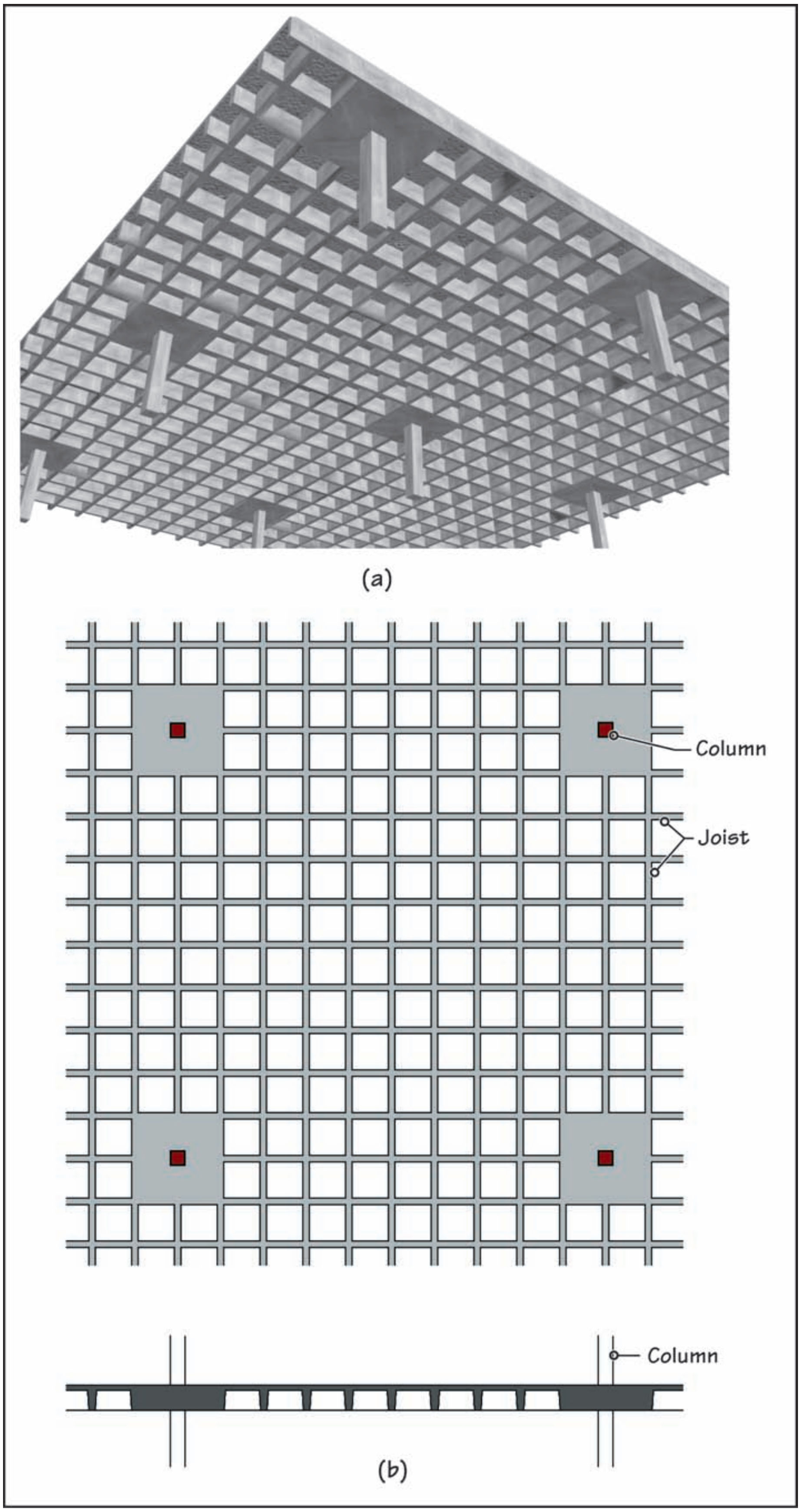


FIGURE 23.15 A beamless waffle slab, that is a waffle slab supported on column heads (capitals). Note the similarity with a flat slab of Figure 23.17. **(a)** Isometric from below. **(b)** Plan (looking up) and section through the slab. Note that a waffle slab can also be constructed with beams, as shown in Figure 23.13. A beamless waffle slab may be provided with spandrel beams, if needed.

FLAT PLATE

A flat plate consists of a solid slab supported directly on columns, Figure 23.16. A flat plate is similar to a two-way banded slab, except that the beam bands in both directions are concealed within the thickness of the slab. Therefore, the spans that can be achieved economically with a flat-plate floor are smaller than those obtained from one-way or two-way joist floors.

Flat-plate slabs are suitable for occupancies with relatively light live loads, such as hotels, apartments, and hospitals, where small column-to-column spacing does not pose a major design constraint. Additionally, a drop ceiling is not required in these occupancies and HVAC ducts can be run within the corridors, where a lower ceiling height is acceptable.

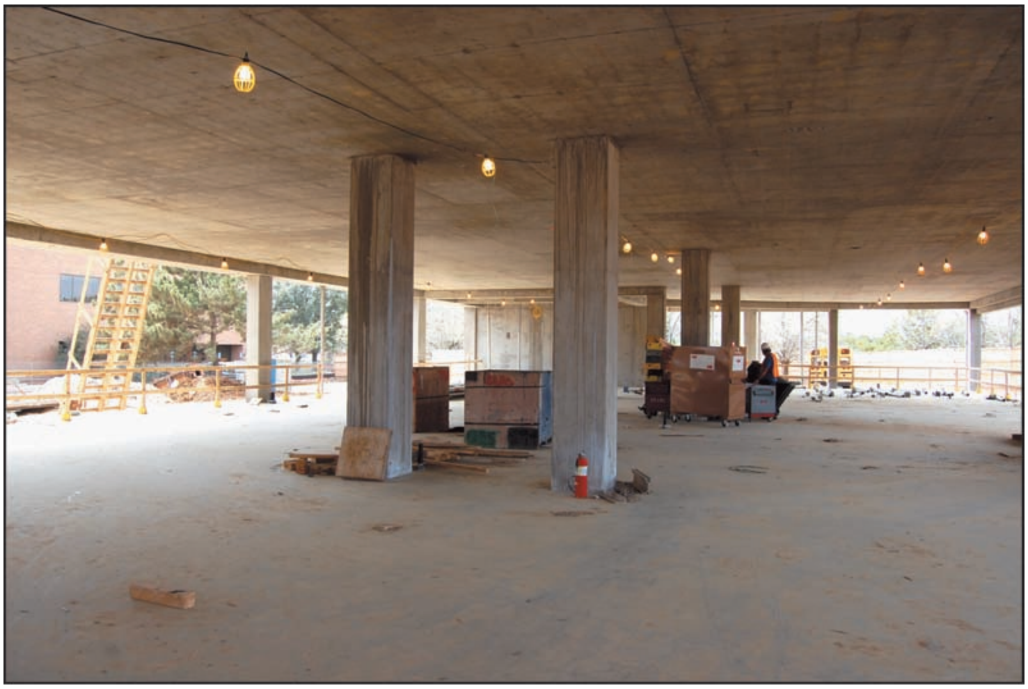


FIGURE 23.16 A flat-plate slab in an office building under construction. Observe the use of perimeter beams, which may be required with heavy exterior wall cladding. Flat-plate slabs without perimeter beams are common. Columns may be rectangular, square, or round.

A flat-plate slab results in a low floor-to-floor height, and its formwork is economical. Because the beams are concealed within the slab thickness, columns need not be arranged on a regular grid—a major architectural advantage. However, a flat plate is a two-way system; hence, the column spacing in both directions should be approximately the same. A slab thickness of approximately 6 in. is generally needed for 15-ft × 15-ft column bays and approximately 8 in. for 20-ft × 20-ft bays with residential loads.

FLAT SLAB

A *flat slab* is similar to a flat plate, but it has column heads, referred to as *drop panels*, Figure 23.17(a). The primary purpose of drop panels is to provide greater shear resistance at the columns, where the shear maximizes.

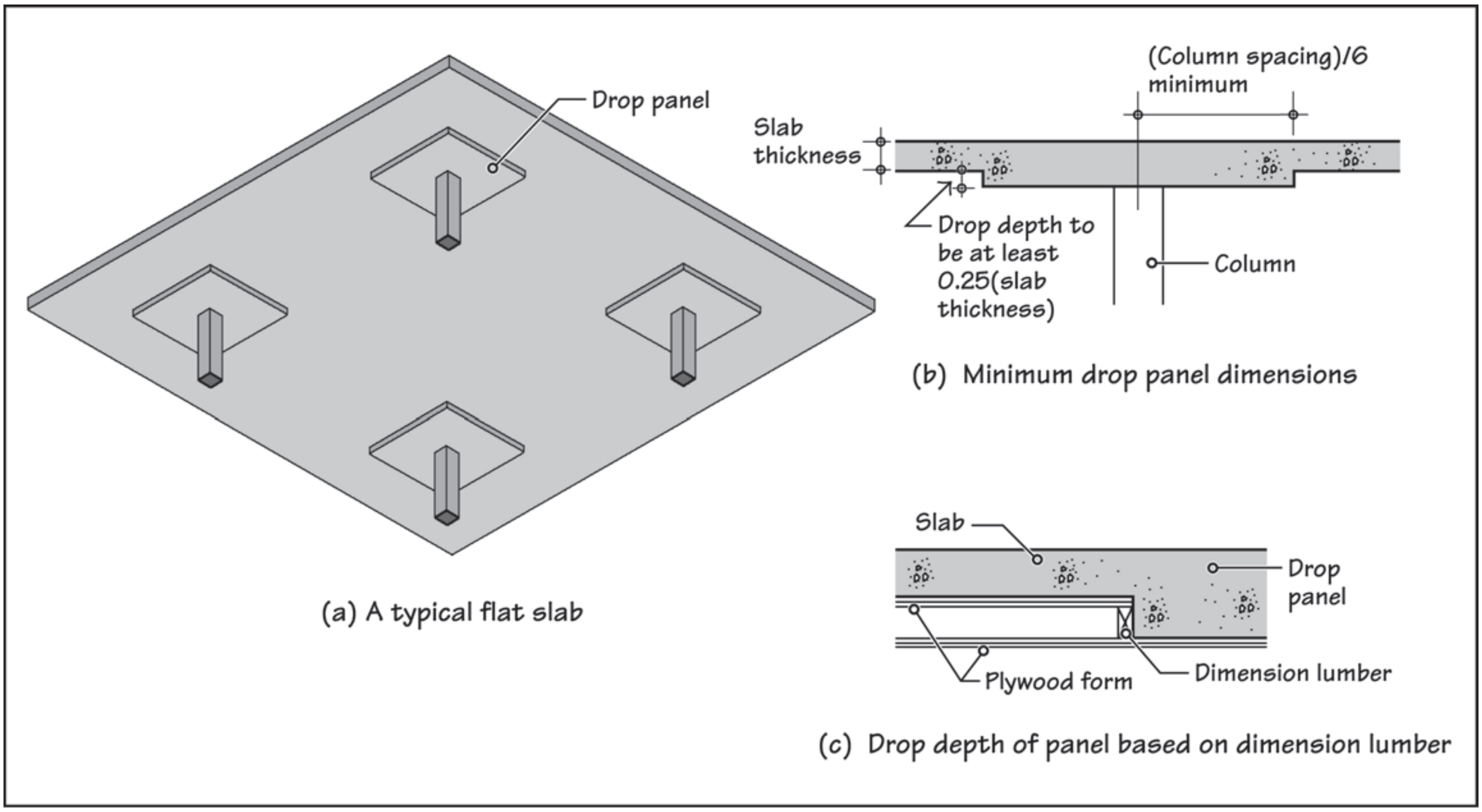
NOTE

Preliminary Depths of Flat-Plate and Flat-Slab Floors

Estimate the depth of a flat-plate floor by dividing the longer clear distance between columns by 30. Thus, if the distance between columns is 20 ft, use an 8-in.-thick slab.

For a flat-slab floor, estimate the thickness of the slab by dividing the longer clear distance between columns by 35. Thus, if the distance between columns is 24 ft, use an 8-in.-thick slab.

Also see Appendix B, and consult a structural engineer for exact sizes.


Drop panel
Slab thickness
(Column spacing)/6 minimum
Drop depth to be at least 0.25(slab thickness)
Column
Slab
Drop panel
Plywood form
Dimension lumber

(a) A typical flat slab

(b) Minimum drop panel dimensions

(c) Drop depth of panel based on dimension lumber

FIGURE 23.17 Typical details of a flat slab and minimum code requirements for drop panel dimensions.

Structurally, the drop panel must extend a minimum of one-sixth of the slab span in each direction, and its drop below the slab must at least be 25% of the slab thickness, Figure 23.17(b). For formwork economy, the drop depth is also based on lumber dimensions, Figure 23.17(c). With round columns, however, manufacturers supply column forms that have built-in drop panels and column capitals, Figure 23.18.

A flat slab is generally used where the live loads are relatively high, such as in parking garages or storage or industrial facilities.

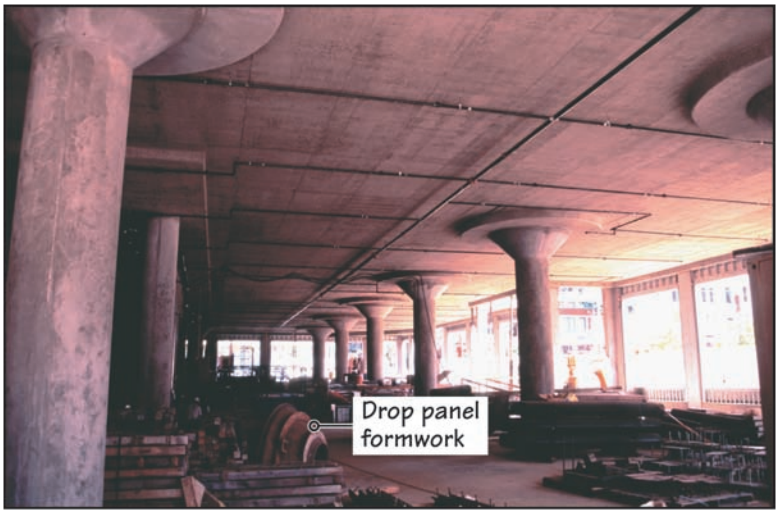


FIGURE 23.18 A flat slab with (round) drop panels and column capitals under construction.

23.4 POSTTENSIONED ELEVATED CONCRETE FLOORS

The reinforced-concrete elevated-slab systems described previously can also be posttensioned. The posttensioning of slabs reduces slab and beam dimensions, reducing the dead load of the floor. This is particularly helpful in seismic areas, where a lower dead load imparts a lower seismic load on the structure. Smaller slab and beam dimensions also result in a lower floor-to-floor height, reducing the cost of exterior cladding. Column and foundation sizes are also reduced.

Because building codes place a limit on the maximum amount of prestress that can be introduced, an elevated, posttensioned concrete slab has a significant amount of conventional reinforcement as well, Figure 23.19. However, the amount of conventional reinforcement in a posttensioned slab is lower than that required if the slab were not posttensioned, reducing reinforcement congestion in long-span and/or heavily loaded members.

Generally, the prestressing (posttensioning) tendons in a slab are distributed in a *banded arrangement* rather than being individually distributed throughout the span in a *basket-weave arrangement*. Generally, the tendons are grouped together along the support lines in one direction, and bands of tendons are placed at equal spacings in the transverse direction, Figure 23.20.

Posttensioned (PT) concrete floors are being increasingly favored for all types of structures—parking garages, high-rise office buildings, hospitals, and condominiums. Figure 23.21 shows a one-way joist floor with PT supporting beams. Posttensioning reduces the depth of beams, which may be necessary in some situations to equalize the depth of the beams with those of the joists. The process of posttensioning in an elevated structure is similar to that of a PT slab-on-ground, covered in Chapter 22.

NOTE

Two Most Commonly Used Concrete Floor Systems

Although various site-cast concrete floor systems have been described in this text, the two most economical floor systems are the *flat-plate floor* and the *one-way joist floor*. For typical live loads of 50 psf, the one-way flat-plate floor is economical for spans of up to approximately 30 ft. For spans between 30 ft and 50 ft, a one-way joist floor is economical [Ref. 23.1].

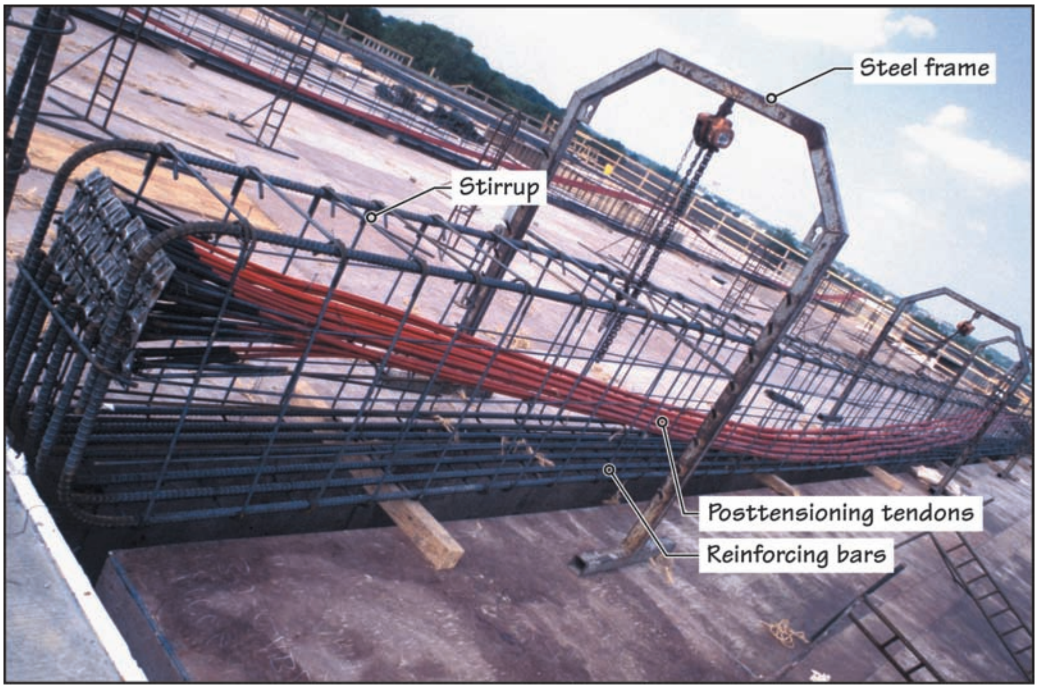


FIGURE 23.19 A cage for a concrete beam consisting of conventional reinforcement and posttensioning tendons (red color) ready to be lowered into the beam form. Observe the drape (generally parabolic) provided in posttensioning tendons to balance the stresses created by gravity loads on the beam. The steel frames shown are used to make the cage. They will be removed after the cage has been placed in the form. Reinforcement for the slab is yet to be completed. Figure 23.20 shows the same beam after its reinforcement has been lowered and the reinforcement and posttensioning tendons for the slab are in place.

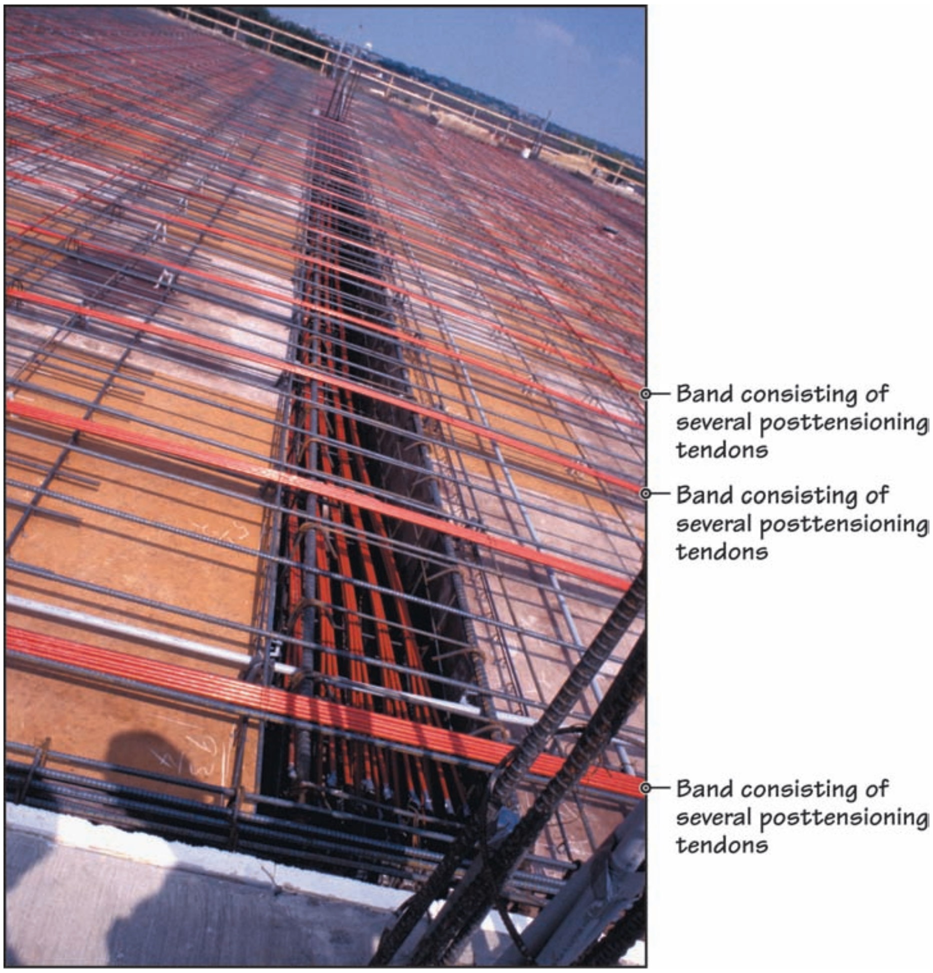

Band consisting of several posttensioning tendons
Band consisting of several posttensioning tendons
Band consisting of several posttensioning tendons

FIGURE 23.20 Layout of reinforcement and posttensioning tendons (red color) in the slab of a building. The reinforcement and posttensioning tendons for the beam are shown in Figure 23.19. Note the banded arrangement of tendons in the slab.

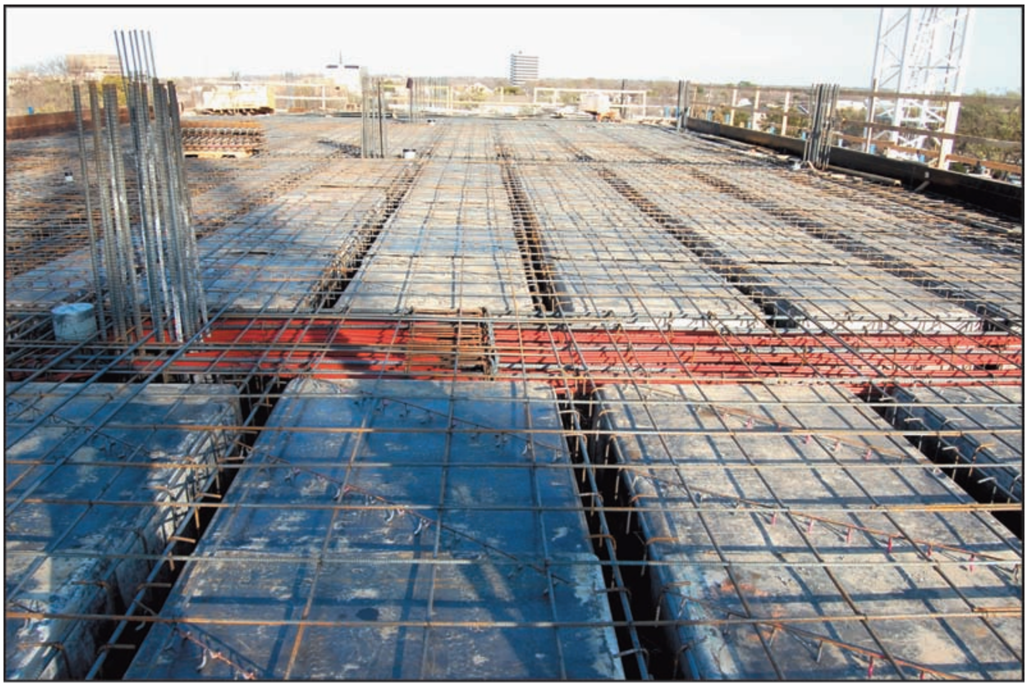


FIGURE 23.21 A wide-module, one-way joist floor with posttensioned (PT) supporting beams. Note the use of (conventional) reinforcement in the slabs and joists. The beams have both conventional reinforcement and posttensioning tendons (red color). PT beams are commonly used in a one-way joist floor to reduce beam size so that joists and beams have the same depth.

23.5 INTRODUCTION TO PRECAST CONCRETE

As stated in the introduction to Chapter 22, precast concrete members (except concrete tilt-up walls) are fabricated in a precast plant and transported to the construction site for assembly. Precasting, which is generally done in covered or sheltered spaces, is particularly helpful in climates that limit the use of site-cast concrete.

Additionally, because precasting is done at the ground level, the cost of formwork and shoring is considerably reduced. Formwork cost reduction is also achieved through the use of standard-size elements cast in permanent forms, which are reused several times more than the formwork used for site-cast members. Precasting also allows greater quality control over the strength of concrete and surface finishes. Most surface finishes are more easily obtained in a precast plant than at the site—often several floors above ground.

Precast elements used as horizontal framing members are generally prestressed (i.e., pretensioned). To ensure rapid reuse of forms and prestressing equipment, Type III (high-early-strength) concrete is generally used with a relatively higher-strength concrete (5,000 to 6,000 psi). To accelerate the setting and hardening of concrete, members are steam cured. Consequently, most precast concrete members are made on a 24-h cycle.

Precast concrete also has many disadvantages. Its main disadvantage is the cost of transportation. Although precast members are generally lighter than corresponding site-cast members (because of prestressing), they are still fairly heavy. Transportation also limits the length and width of precast members.

Another disadvantage of precasting is the need for heavier hoisting equipment at the construction site and additional safety measures that must be observed during erection. Erection and assembly at the site also introduce the need for a more skilled workforce compared with site-cast concrete construction. Architecturally, the most limiting factor in the use of precast concrete is the difficulty in sculpting concrete at a large scale, which is more easily realized with site-cast concrete. Precast elements are generally straight, with standard profiles.

ARCHITECTURAL PRECAST AND STRUCTURAL PRECAST CONCRETE

Precast concrete members are classified as: (a) *architectural precast concrete* and (b) *structural precast concrete*. *Architectural precast* refers to concrete elements that are used as nonstructural cladding elements. Their most common use is in precast concrete curtain walls (see Chapter 28).

Structural precast concrete, which is covered in this chapter, includes all elements of a building's structural frame (floor/roof slabs, columns, and walls). Although an entire room or assembly of rooms can be precast, most structural precast concrete is used in standard elements that are assembled on site to form spaces.

STRUCTURAL PRECAST—TOTAL PRECAST AND MIXED PRECAST CONSTRUCTION

A building can be constructed of all precast concrete members in which all structural components—columns, load-bearing walls, and floor and roof slabs—are of precast concrete. This system is referred to as total *precast concrete construction*. In mixed precast construction, some elements of the building consist of precast concrete members, while the others are of cast-in-place concrete, steel, or masonry.

Mixed precast construction is far more common than total precast. It combines the benefits of both precast and conventional construction. In mixed precast, precast concrete is used only in floor and roof slabs. Using precast concrete floor/roof slabs yields significant savings because a large percentage of the cost of materials and formwork in a concrete structure is embedded in floor and roof slabs (see Section 23.1).

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

13. A flat slab floor consists of
- **a.** a slab of constant thickness.
- **b.** a slab with beams on all four sides of the slab panel.
- **c.** a slab with drop panels at each column.
- **d.** none of the above.

14. A flat plate floor consists of
- **a.** a slab of constant thickness.
- **b.** a slab with beams on all four sides of the slab panel.
- **c.** a slab with drop panels at each column.
- **d.** none of the above.

15. Commonly used beamless concrete floors are
- **a.** one-way and two-way joist floors.
- **b.** flat-plate and flat-slab floors.
- **c.** beam-and-girder floors.
- **d.** all of the above.

16. In a posttensioned elevated concrete floor, prestressing tendons are combined with conventional steel reinforcement.
- **a.** True
- **b.** False

17. The primary reason for using posttensioned concrete floors is to
- **a.** reduce or prevent the cracking of concrete.
- **b.** improve safety against failure.
- **c.** reduce floor depth.
- **d.** reduce or prevent corrosion of reinforcement.
- **e.** reduce formwork cost.

18. The strength of concrete used in precast concrete members is generally
- **a.** 1 ksi to 2 ksi.
- **b.** 2 ksi to 3 ksi.
- **c.** 3 ksi to 4 ksi.
- **d.** 4 ksi to 5 ksi.
- **e.** 5 ksi to 6 ksi.

19. Portland cement used in precast concrete members is generally
- **a.** Type V.
- **b.** Type IV.
- **c.** Type III.
- **d.** Type II.
- **e.** Type I.

20. Architectural precast concrete refers to concrete members used in building interiors.
- **a.** True
- **b.** False

23.6 STRUCTURAL PRECAST CONCRETE MEMBERS

Structural precast concrete members may be classified as

- Horizontal-spanning elements: These consist of: (a) hollow-core slabs, (b) solid planks, (c) double-tee units, and (d) inverted-tee beams.
- Vertical-spanning members: These consist of: (a) columns and (b) walls.

Horizontal-spanning elements are almost always prestressed, and vertical spanning elements are generally not prestressed. A brief description of horizontal-spanning members and their use in mixed precast construction follows.

HOLLOW-CORE SLABS AND SOLID PLANKS

Hollow-core slabs are precast, prestressed concrete slabs that contain voids in their central region. The voids reduce the dead load of the slab by 40% to 50% compared with a site-cast concrete slab for the same span.

Hollow-core slabs are produced in thicknesses of 4 in., 6 in., 8 in., 10 in., 12 in., and 14 in., with the 8-in.-thick slab being most commonly used. The width of the slabs is generally 4 ft. Narrow-width slabs are produced in the plant by cutting standard 4-ft slabs along their length to fit a space that is not a multiple of 4 ft. In addition to 4-ft-wide slabs, some plants make slabs that are 3 ft 4 in. and 8 ft wide.

Figure 23.22 shows a typical section through an 8-in.-thick, 4-ft-wide hollow-core slab. The number of voids and their cross-sectional profiles are manufacturer specific. Manufacturers provide the load capacity of their slabs, along with suggested details for connecting the slabs with supporting members.

Hollow-core slabs are generally used in mixed precast buildings, where the supporting structure may be of steel, masonry or site-cast concrete. Figure 23.23 shows the use of hollow-core slabs in a steel-frame building. Their use with a site-cast concrete frame is shown

NOTE

Approximate Spanning Capability of Hollow-Core Slabs

To determine the approximate thickness of a hollow-core slab floor, divide the span by 40. Thus, if the distance between supporting members is 25 ft, the thickness of a hollow-core slab is (25 × 12)/40 = 7.5 in. Hence, use an 8-in. slab. A 12-in. slab has an approximate spanning capability of 40 ft.

Due to lighter loads on roofs, the slab thickness for roofs may be determined by dividing the span by 50.

Also see Appendix B, and consult a structural engineer for exact sizes.

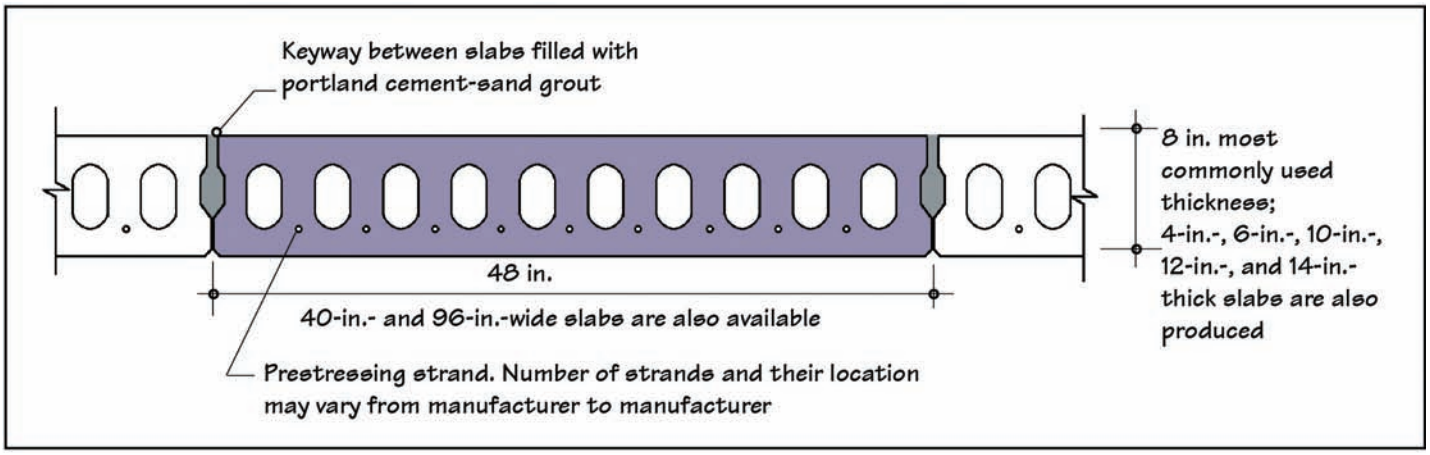

Keyway between slabs filled with portland cement-sand grout
8 in. most commonly used thickness; 4-in.-, 6-in.-, 10-in.-, 12-in.-, and 14-in.-thick slabs are also produced
48 in.
40-in.- and 96-in.-wide slabs are also available
Prestressing strand. Number of strands and their location may vary from manufacturer to manufacturer

FIGURE 23.22 A typical section through a 4-ft-wide, 8-in.-thick hollow-core slab. The dimensions of voids, their number, and profile are manufacturer-specific.

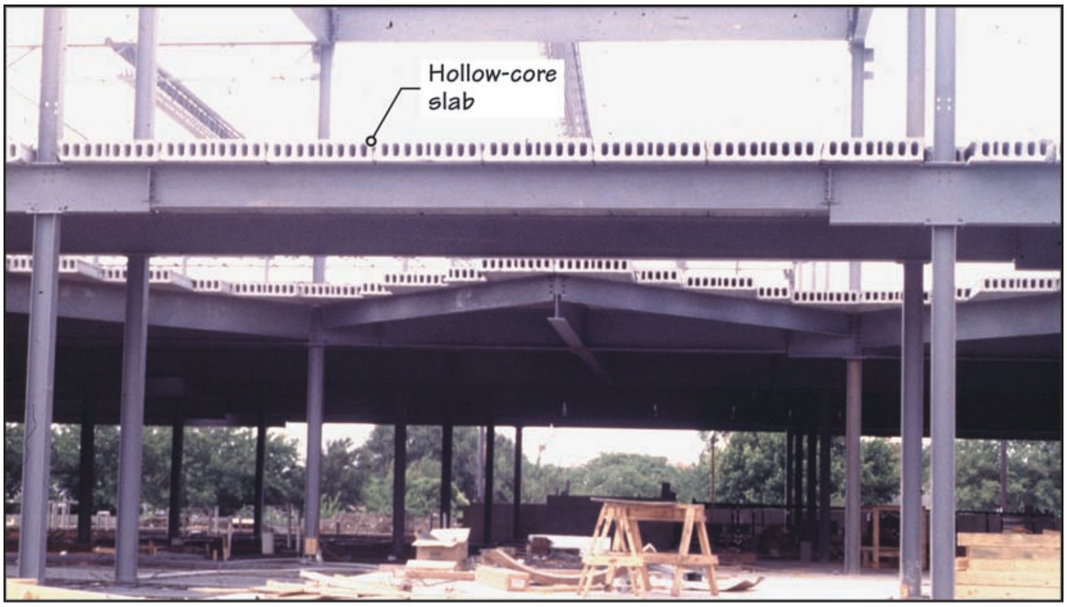

Hollow-core slab

FIGURE 23.23 Mixed precast concrete construction consisting of a steel-frame structure with hollow-core slabs.

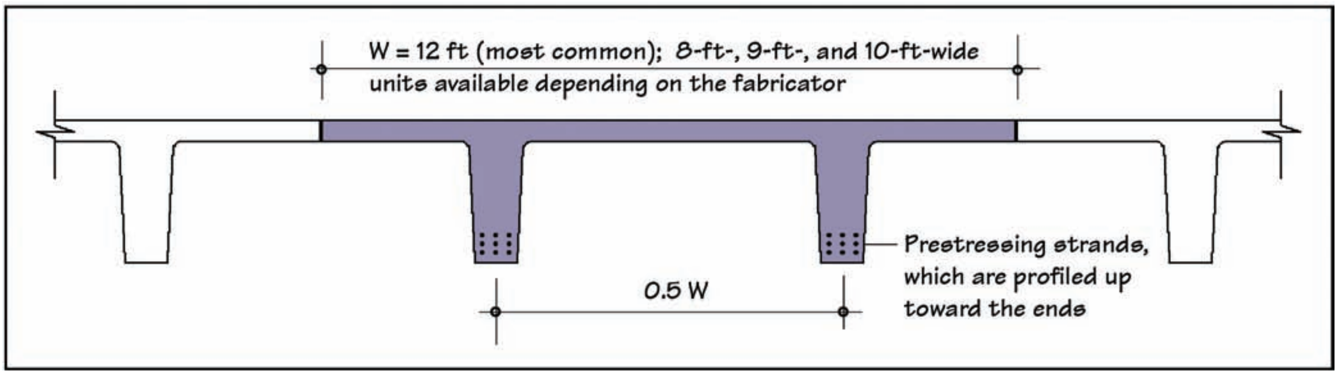

W = 12 ft (most common); 8-ft-, 9-ft-, and 10-ft-wide
units available depending on the fabricator
0.5 W
Prestressing strands,
which are profiled up
toward the ends

FIGURE 23.24 Typical section through a double-tee floor.

in Chapter 12 (Figure 12.34); Chapter 26 (Sections 26.5 and 26.6) shows their use in load-bearing masonry structures.

Connections between hollow-core slabs and supporting members are made using site-cast concrete fill and reinforcing steel (see Sections 26.5 and 26.6). In addition to the concrete fill used for connections, a site-cast concrete topping is generally used over the slabs. The topping provides structural integration of slab units and increases the floor's fire resistance and sound insulation. It also functions as a leveling bed, particularly with units with uneven camber. In many buildings, however, topping is omitted for the sake of economy. Topping, when used, is generally 2 in. to $2\frac{1}{2}$ in. thick and reinforced with welded wire reinforcement (WWR).

Hollow-core slabs are produced through a long-line extrusion process. The machine, housed in a precasting enclosure, lays concrete on a casting bed over prestressing tendons, which have already been pretensioned to the required level of stress. It forms continuous voids as it travels along the length of the bed. The concrete used is high-strength, zero-slump concrete.

After casting, the slab is steam cured and cut to customer-specified lengths. The cut lengths of slabs are removed from the bed the morning after casting, and the process just described is repeated on a 24-h basis.

Solid precast concrete planks are similar to hollow-core planks and are generally used where superimposed loads are relatively light.

NOTE

Approximate Spanning Capability of Double-Tee Units

To determine the approximate depth of a double-tee unit floor, divide the span by 28. Thus, if the span of units is 60 ft, the approximate depth of the floor is (60 × 12)/28 = 26 in.

Standard available depths of double-tee units are generally 14 in., 18 in., 24 in., and 30 in. The manufacturer should be consulted for more precise information.

Also see Appendix B, and consult a structural engineer for exact sizes.

DOUBLE-TEE UNITS

A typical section through a double-tee unit is shown in Figure 23.24. The width of units is generally 8 ft, with a center-to-center distance of 4 ft between beams. Double-tee units with widths of 9 ft, 10 ft, and 12 ft are also available from some manufacturers. Overall depths of double-tee units vary from 16 in. to 36 in. to give different spanning capabilities.

Double-tee units are used where the spans are large and cannot be provided economically with site-cast concrete construction or hollow-core slabs. They are commonly used for hotel and bank lobbies. As with hollow-core slabs, a topping of concrete and WWR may be used on double-tees for structural integration and leveling.

Another common use of double-tees is in multistory parking garages, where a minimum distance of 60 ft between columns is generally necessary. In garages, double-tees are generally supported on site-cast or precast inverted T-beams. Double-tee units are cast on a long line of steel formwork. Several units are made in one casting operation by dividing the bed with separators.

NOTE

Single-Tee Units

Single-tee units were used formerly (generally for long spans), but they are not commonly used today because of erection instability problems.

INVERTED-TEE BEAMS

Precast inverted-tee beams are generally used as supporting members for hollow-core slabs or double-tee units. Like hollow-core slabs and double-tee units, they are prestressed. They are commonly used in total precast construction (see Figure 23.28).

23.7 TOTAL PRECAST CONCRETE CONSTRUCTION

Figure 23.25 shows a total precast building under construction, whose structural frame comprises double-tee units, inverted-tee beams, columns, and walls. The construction process of a total precast building has much in common with structural steel construction; that is, members are brought into position using a crane, as seen in Figure 23.26, and are connected together either through welds or bolts. Steel embeds are included in precast members to facilitate member bolting and/or welding.

Figure 23.27(a) shows the top of a lower-floor column with threaded bolts projecting out, and Figure 23.27(b) shows the bottom of an upper-floor column with an embedded base

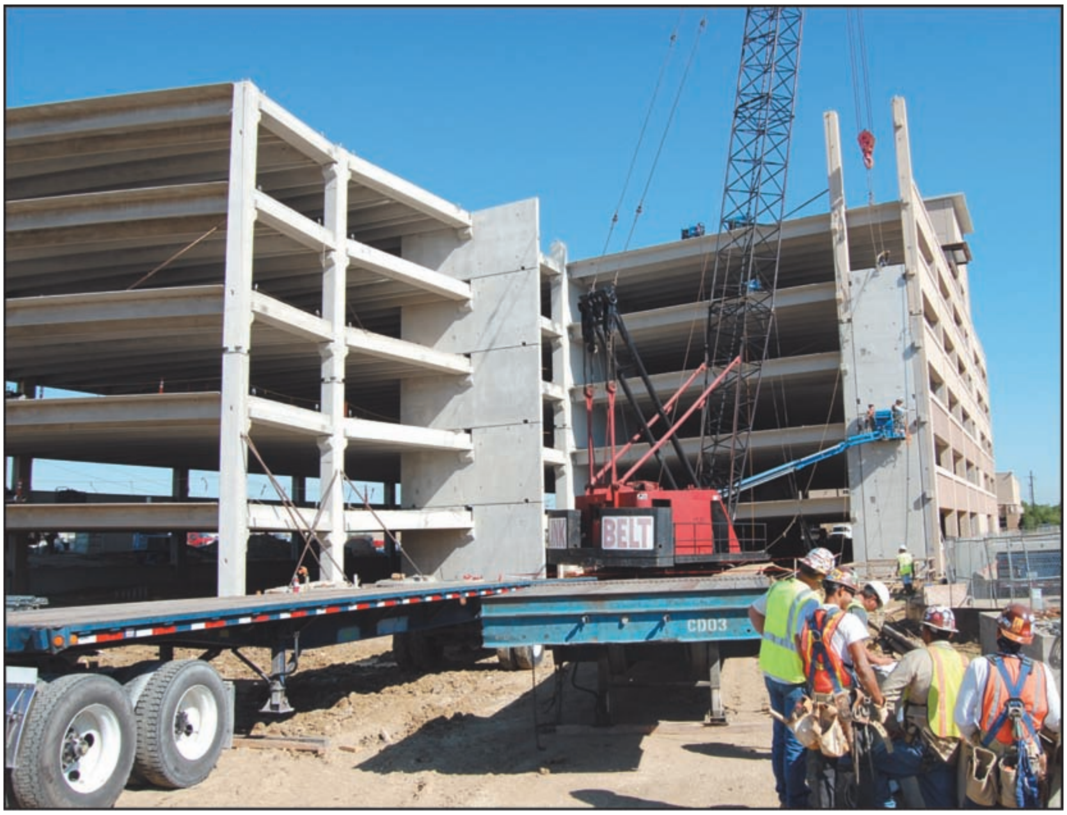


FIGURE 23.25 A total precast concrete parking garage under construction.

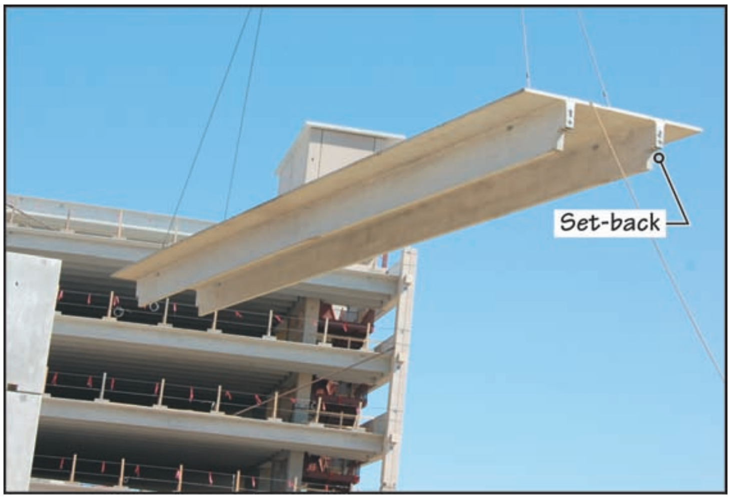


FIGURE 23.26 A double-tee floor unit being flown into position in the total precast building in Figure 23.25. The setbacks in double-tee stems reduce floor height.

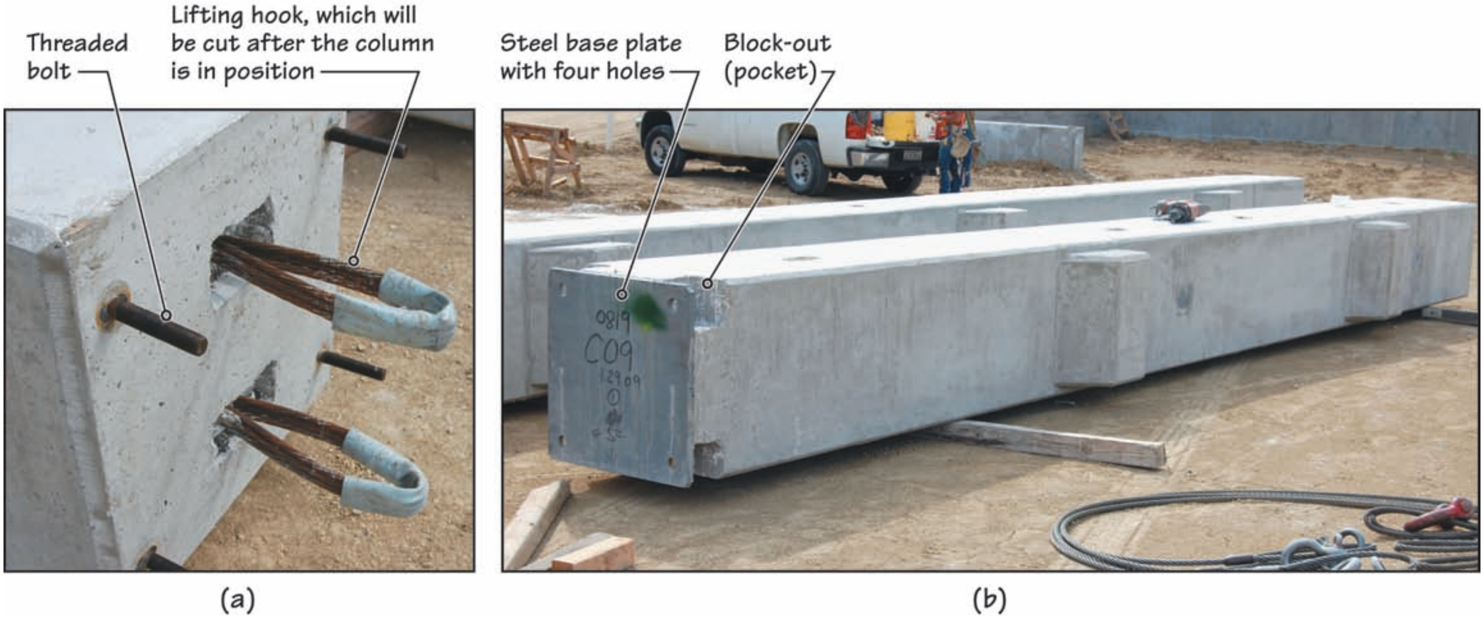

Threaded bolt
Lifting hook, which will be cut after the column is in position
Steel base plate with four holes
Block-out (pocket)
(a)
(b)

FIGURE 23.27 **(a)** Top of the lower-floor column with threaded bolts. **(b)** Bottom of the upper-floor column (two stories high). The block-outs (pockets) in the columns allow a bolted connection between the lower- and upper-floor columns.

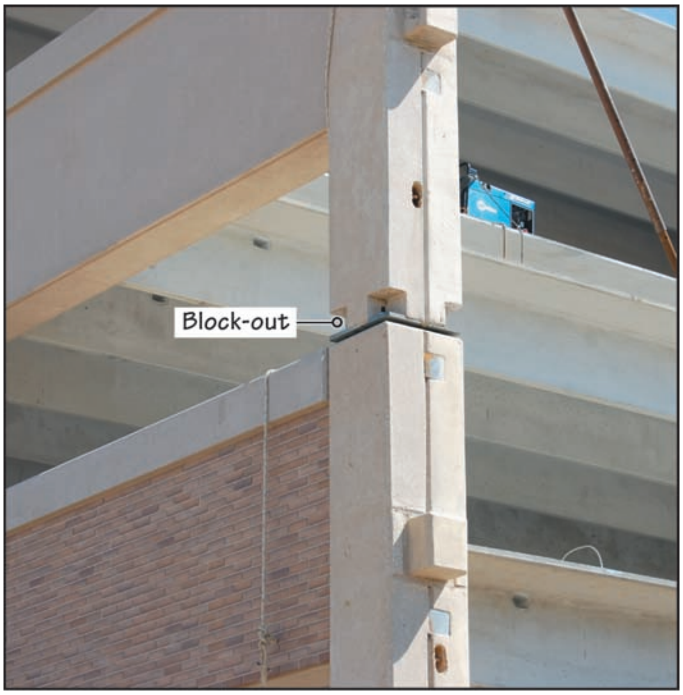


FIGURE 23.28 Close-up of the bolted connection between the lower- and upper-floor columns. The block-outs (pockets) will be filled with concrete and finished smooth to match the column surface.

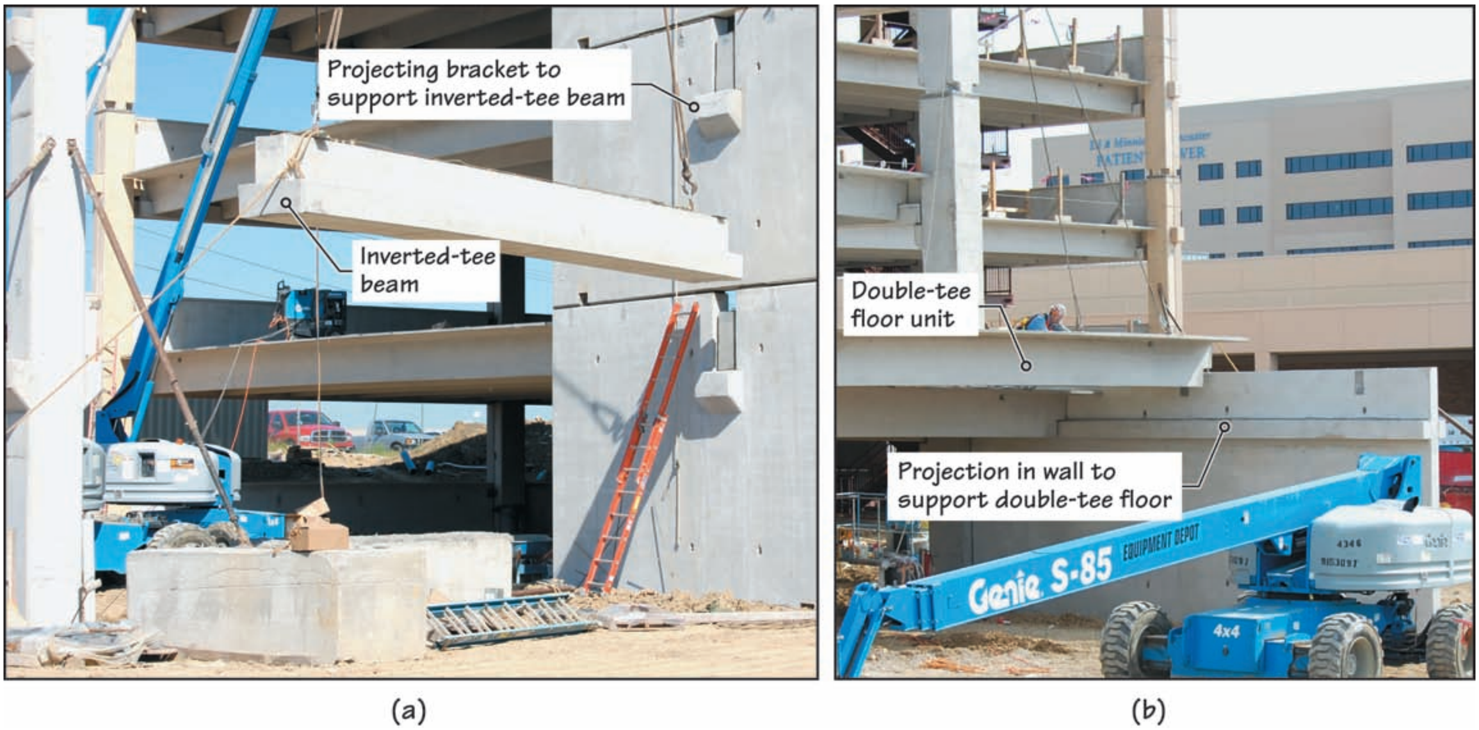

Projecting bracket to support inverted-tee beam
Inverted-tee beam
Double-tee floor unit
Projection in wall to support double-tee floor
Genie S-85
(a)
(b)

FIGURE 23.29 Projections in precast concrete walls to support **(a)** inverted-tee beams and **(b)** double-tee floor slabs.

plate containing holes to engage the bolts. The block-outs in the column above the holes are filled with concrete after the connection has been made. Figure 23.28 shows a close-up of the connection between the lower- and upper-floor columns.

Walls in a total precast building carry gravity loads and also function as shear walls. Where needed, the walls are provided with projecting brackets to receive inverted-tee beams, Figure 23.29(a) or double-tee units, Figure 23.29(b).

23.8 FIRE RESISTANCE OF CONCRETE MEMBERS

The fire resistance of a concrete member is a function of three variables:

- Thickness of the member
- Type of coarse aggregate
- Cover over reinforcement and prestressing tendons

TABLE 23.1 FIRE RESISTANCE OF CONCRETE MEMBERS

		Fire resistance		
Member	**Aggregate type**	**1 h**	**2 h**	**3 h**
Minimum thickness (in.) of floor slabs or walls	Lightweight	2.5	3.6	4.4
	Carbonate	3.2	4.6	5.7
	Siliceous	3.5	5.0	6.2
Minimum thickness (in.) of columns	Lightweight	8	9	10.5
	Carbonate	8	10	11
	Siliceous	8	10	12

A thicker member has greater fire resistance. For the same member thickness, a lightweight aggregate gives greater fire resistance than a normal-weight aggregate. Among the normal-weight aggregates, carbonate aggregate (i.e., limestone) gives greater fire resistance than noncarbonate (i.e., siliceous) aggregates.

Local building codes prescribe the minimum thickness of members to achieve a given fire resistance, Table 23.1. In addition to meeting minimum thickness requirements, the member must satisfy minimum cover requirements. The minimum cover required for corrosion protection (Table 19.1) is adequate to satisfy the fire-resistance requirements in most situations. However, the local building code must be referenced for precise information.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

21. In mixed precast construction, precast concrete members are generally used for
- **a.** shear walls.
- **b.** load-bearing walls.
- **c.** columns.
- **d.** floors.
- **e.** all of the above.

22. In total precast construction, precast concrete members are generally used for
- **a.** shear walls.
- **b.** load-bearing walls.
- **c.** columns.
- **d.** floors.
- **e.** all of the above.

23. A 12-in.-thick hollow-core floor slab will generally span up to approximately
- **a.** 40 ft.
- **b.** 30 ft.
- **c.** 25 ft.
- **d.** 20 ft.
- **e.** none of the above.

24. When a concrete topping is used over hollow-core slabs, its thickness is approximately
- **a.** 1 in.
- **b.** $1\frac{1}{2}$ in.
- **c.** 2 in.
- **d.** 3 in.
- **e.** 4 in.

25. The purpose of concrete topping on hollow-core slabs is to
- **a.** structurally integrate the slabs.
- **b.** level the top of slabs.
- **c.** increase the sound insulation of the floor.
- **d.** increase the fire rating of the floor.
- **e.** all of the above.

26. The most commonly used width of a double-tee floor unit is
- **a.** 8 ft.
- **b.** 6 ft.
- **c.** 4 ft.
- **d.** none of the above.

27. Double-tee floors are commonly used
- **a.** in residential occupancies.
- **b.** where spans lie between 30 ft and 40 ft.
- **c.** where spans lie between 40 ft and 50 ft.
- **d.** where spans are in excess of 50 ft.

28. The fire-resistance rating of concrete members is a function of
- **a.** member thickness.
- **b.** type of coarse aggregate in concrete.
- **c.** concrete cover for corrosion protection.
- **d.** all of the above.

EXPAND YOUR KNOWLEDGE

Building a Separation Joint in a Site-Cast Concrete Building

As discussed in Chapter 9, continuous building separation joints are required in many buildings. A preferred method is to use two columns and two beams at the joint. Often for the sake of economy, however, a single column with two beams is used. The following text explains the construction of such a joint in a site-cast, reinforced-concrete building. (See Chapter 19 for similar detail in a steel-frame building.)

(*Continued*)

EXPAND YOUR KNOWLEDGE *(Continued)*

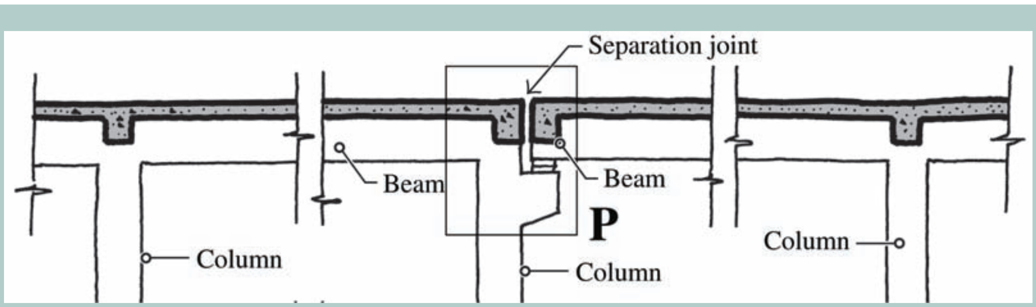

Separation joint
Beam
Beam
P
Column
Column
Column

FIGURE 1 Section through a concrete floor at a building separation joint using one column at the joint (also see Chapter 9).

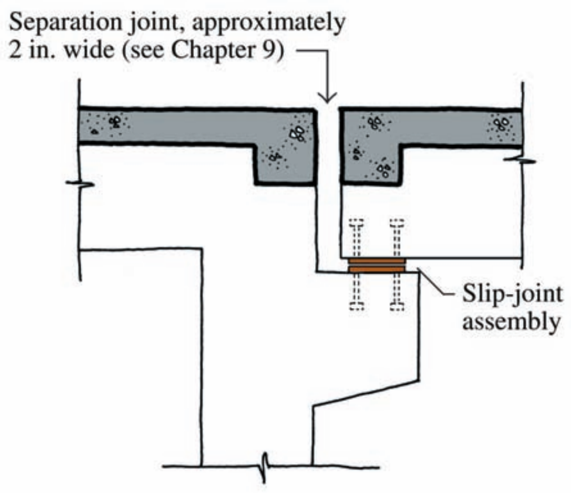

Separation joint, approximately 2 in. wide (see Chapter 9)
Slip-joint assembly

FIGURE 2 Detail P.

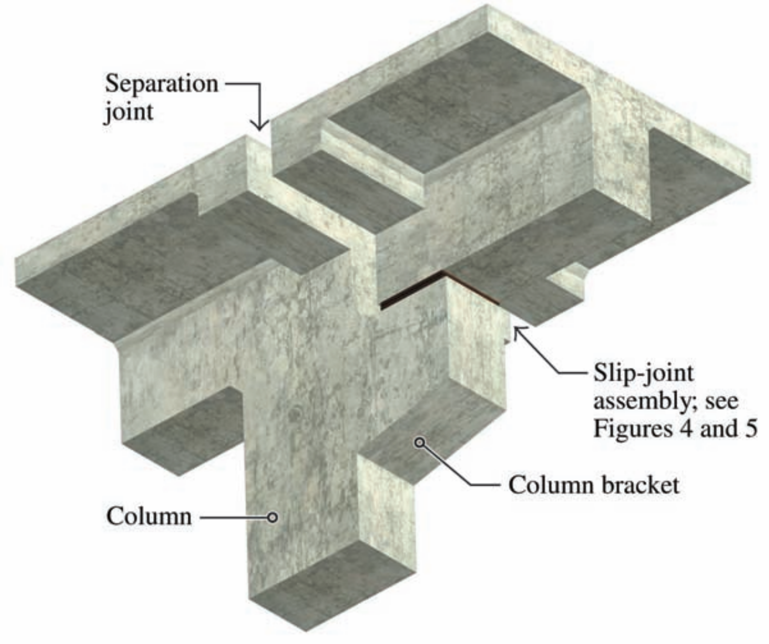
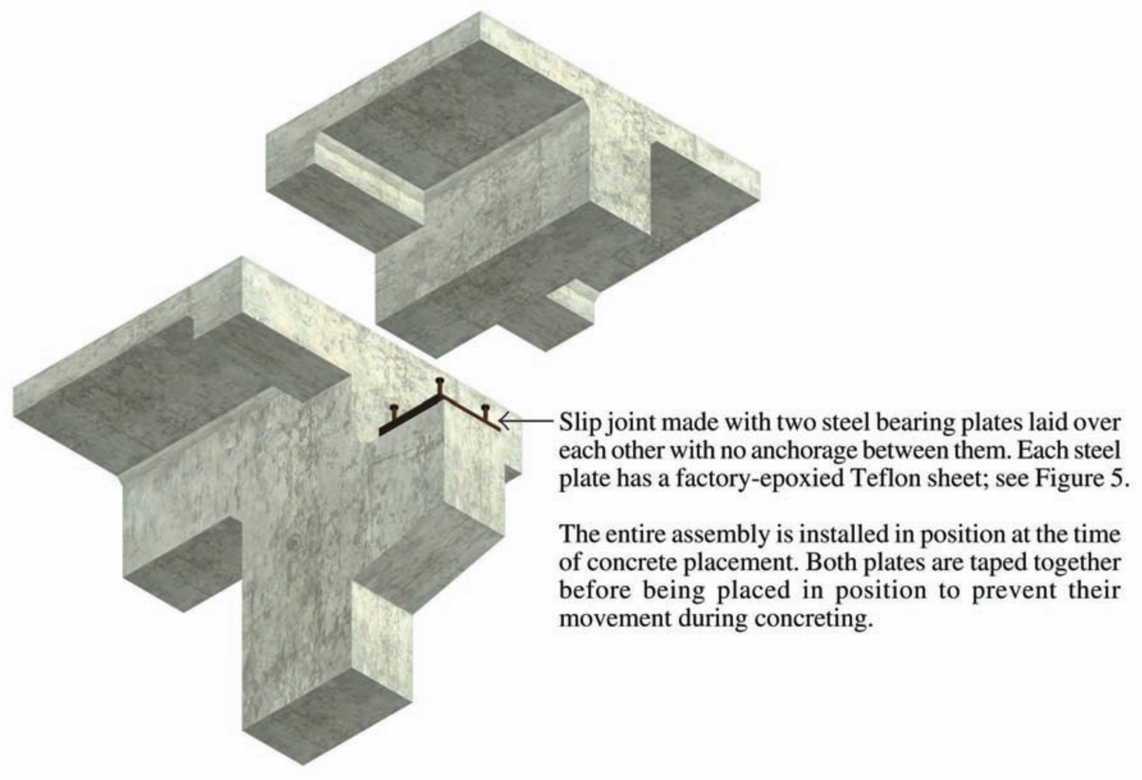

Separation joint
Slip-joint assembly; see Figures 4 and 5
Column bracket
Column

FIGURE 3 Three-dimensional view of Detail P.

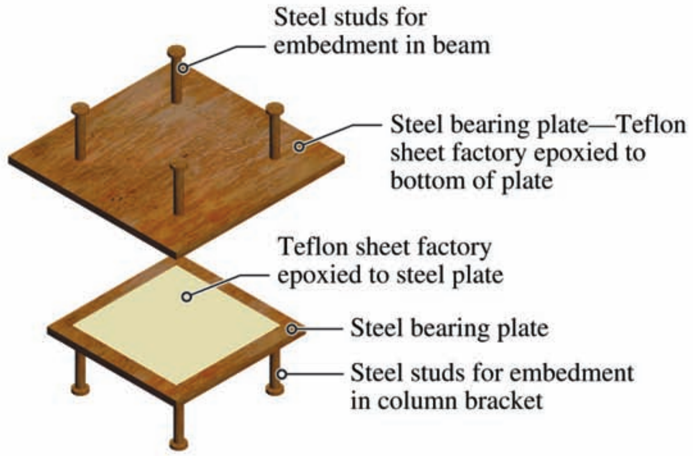


Slip joint made with two steel bearing plates laid over each other with no anchorage between them. Each steel plate has a factory-epoxied Teflon sheet; see Figure 5.

The entire assembly is installed in position at the time of concrete placement. Both plates are taped together before being placed in position to prevent their movement during concreting.

FIGURE 4 Detail of the slip joint at P.

EXPAND YOUR KNOWLEDGE


Steel studs for embedment in beam
Steel bearing plate—Teflon sheet factory epoxied to bottom of plate
Teflon sheet factory epoxied to steel plate
Steel bearing plate
Steel studs for embedment in column bracket

Each steel bearing plate is factory epoxied to a Teflon sheet. Teflon sheet is used because of its very low coefficient of friction which allows movement between the column bracket and the concrete beam above.

Although the plates have been shown separated from each other, they are taped together before being placed in position. The upper plate is slightly larger than the lower plate to provide protection to the Teflon sheet and to allow the space between the plates to be filled with an elastomeric sealant (also see Figure 19.22).

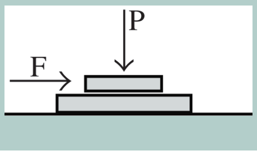
FIGURE 5 Bearing plates in a slip-joint assembly.

Coefficient of Friction

Assume that two rectangular blocks are laid, one over the other. A weight, P, is placed on the upper block, which is then made to slide over the lower block with the help of a horizontal force, F. If F is the horizontal force that is just able to slide the upper block, then the *coefficient of friction*, ϕ, between the surfaces of the blocks is given by

$$\phi = \frac{F}{P}$$

If the force required to slide is small, ϕ is small. The value of ϕ between two Teflon sheets is nearly 0.05 (as reported by a separation joint assembly manufacturer, Conserve Inc., Georgetown, South Carolina).



REVIEW QUESTIONS

1. Explain the difference between one-way slab and two-way slab actions.
2. Using sketches and notes, explain beam-and-girder floor systems.
3. Using sketches and notes, illustrate the two most commonly used reinforced-concrete floor systems.
4. Using sketches, explain the commonly used beamless concrete floor systems.
5. Sketch the following precast concrete structural members:
    a. Hollow-core units
    b. Solid planks
    c. Double-tee units
    d. Inverted-tee beams
6. Explain the difference between total precast and a mixed precast construction.

CHAPTER 24

Masonry Materials–I (Mortar and Brick)

CHAPTER OUTLINE

24.1 Masonry Mortar

24.2 Mortar Materials and Specifications

24.3 Mortar Joint Thickness and Profiles

24.4 Manufacture of Bricks

24.5 Dimensions of Masonry Units

24.6 Types of Clay Bricks

24.7 Bond Patterns in Masonry Walls

24.8 The Importance of the Initial Rate of Absorption (IRA) of Bricks

24.9 The Craft and Art of Brick Masonry Construction

24.10 Efflorescence in Brick Walls

24.11 Expansion Control in Brick Walls

Masonry is one of the oldest building materials. Sun-dried clay (adobe) bricks were used as early as 8,000 BC. The origin of stone masonry is generally traced by historians to the early Egyptian and Mesopotamian civilizations, which existed around 3,000 BC. Indeed, until steel and Portland cement were discovered in the mid-nineteenth century, stone was the only building material available for the construction of large building structures and bridges.

The history of architecture is replete with examples of magnificent buildings in which dressed (and partially dressed) stones were used in almost every building element—walls, columns, beams, arches, roofs (vaults and domes), and floors. In some buildings, the stones were so large that historians have differing theories as to the hoisting apparatus used by the builders at the time.

The history of architecture is also a testament to the durability and aesthetics of stone. It is these properties that render stone a matchless material even for present-day buildings, particularly those that require durable and maintenance-free facades, such as the building of Figure 24.1. In fact, together with glass, stone is one of the most-used material for the exterior facades of contemporary skyscrapers.

Whereas stone is uniquely suited for cladding high-rise and significant buildings, other masonry materials, such as brick and block, are more economical facade alternatives and are widely used. If we lump all masonry materials together, we observe that the use of masonry on contemporary building facades exceeds that of all other materials combined.

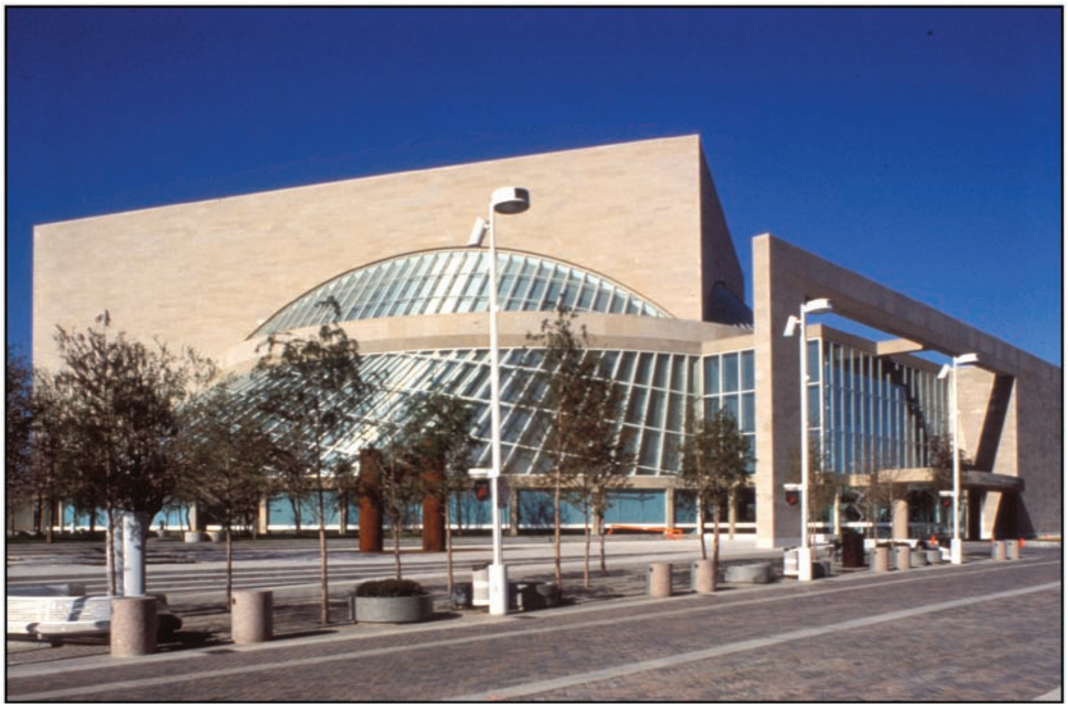


FIGURE 24.1 Smooth-surfaced limestone cladding, Morton Meyerson Symphony Center, Dallas, Texas. Architect: I. M. Pei and Partners.

UNIT MASONRY

Because bricks are generally made from clay, brick masonry is also referred to as *clay masonry*. Block masonry is called *concrete masonry* because the blocks are made from concrete. Because masonry is laid unit by unit (e.g., brick by brick or block by block), it is also referred to as *unit masonry*. Bricks and blocks are, therefore, called *clay masonry units* and *concrete masonry units* (CMU), respectively.

Masonry units are bonded together with mortar to yield a composite building component—generally a wall. Thus, mortar is the common ingredient in all masonry construction. Mortarless masonry, although possible, is uncommon and has relatively few applications; it is not discussed in this text. Because mortar is common to virtually all masonry, we discuss it first, followed by a discussion of bricks. Other masonry materials, including CMU, stone, and glass masonry, are discussed in Chapter 25. Masonry construction systems are discussed in Chapters 26 and 28.

24.1 MASONRY MORTAR

Mortar consists of a binder (cementitious material), a filler, and water. Portland cement and hydrated lime comprise the binder, and the filler is sand. When these three elements are mixed together with the required quantity of water, mortar results.

The primary function of masonry mortar is to bond the masonry units into an integral masonry wall. Because mortar, in its plastic state, is pliable, it molds itself to the surface profile of the units being mortared. This not only helps seal the wall against water and air infiltration, but also provides a cushion between the units.

The mortar cushion also compensates for size variations between individual units. Another important role of mortar is to provide surface character to masonry through shadow lines at mortar joints and color intervention between the units.

WORKABILITY AND WATER RETENTIVITY OF MORTAR: THE ROLE OF LIME

Lime imparts several useful and important properties to the plastic as well as the hardened mortar. In the plastic (wet) state of mortar, lime improves its workability and water retentivity. A mortar comprising Portland cement only (without lime) is coarse and, hence, less workable. In the hardened state, lime improves the water resistance of the wall. A wall built with Portland cement and lime mortar is more watertight than a wall built with only Portland cement mortar.

NOTE

Mortarless Masonry Walls

A common contemporary use of mortarless masonry is in segmental retaining walls. Mortarless masonry is extremely uncommon in a conventional wall.

If a mortarless masonry wall (also called *dry-stacked masonry*) is used in a conventional wall, the units may need grinding to provide a smooth bed surface. To provide bending resistance in a mortarless masonry wall, the voids in the units may be grouted and reinforced, and/or both surfaces of the wall may be coated with a surface-bonding material, such as plaster.

NOTE

Lime for Masonry Mortar

The lime recommended for use in masonry mortar is Type S hydrated lime (see Chapter 21).

In Chapter 21, we observed that the workability of concrete is a quantifiable property. This is not the case with mortar. The workability of mortar is difficult to quantify because it is a function of several interdependent factors. However, a mason with even a limited amount of experience and training can easily distinguish between a workable and a nonworkable mortar.

A workable mortar is cohesive and spreads easily on the units using a trowel. Because of its cohesiveness, it clings to the vertical surfaces of the units and the trowel without sliding down. It extrudes easily so that excess mortar in the joints can be troweled off without the mortar dropping off or smearing the units. A lay (and rather crude) explanation of the difference between a workable and a nonworkable mortar is the difference between spreading a creamy (more workable) and a crunchy (less workable) peanut butter on a piece of toasted bread.

Another important property of plastic mortar is its water retentivity. This is the ability of mortar to retain water without letting it bleed out. A mortar with good water retentivity remains soft and plastic for a long period of time and allows only a limited amount of water to be absorbed by the units.

NOTE

Autogenous Healing

Because a lime-based mortar is somewhat elastic, it is less liable to crack. However, if cracks are formed, the carbonation of lime fills them. In the carbonation process, lime absorbs atmospheric carbon dioxide (see Chapter 21), which increases its mass and volume. The increase helps to fill the voids caused by drying shrinkage of Portland cement and by flexural cracking of masonry—a process known as *autogenous healing*.

The term *autogenous healing* has been borrowed from medicine and refers to the natural healing process of human bones. When a bone in the body fractures, a surgeon simply aligns the fractured parts in their original position and sustains them in that position using a cast. The fractured pieces fuse together automatically in due course. Although the healing of a bone fracture is complex, it is primarily due to the calcium in human bones—similar to the calcium in lime.

Water retentivity and workability are directly related to each other. Extremely fine sand particles, air-entraining agents, and lime increase the workability and water retentivity of mortar. While a certain amount of water absorption by the units is necessary for the bond between the mortar and the units, excessive water retentivity is to be avoided because it reduces the strength of the bond.

WATERTIGHTNESS OF A MASONRY WALL: THE ROLE OF LIME

Lime also improves the elasticity of hardened mortar. In other words, a lime-based mortar is able to flex somewhat in its hardened state. This reduces the cracks caused by the bending of a wall under lateral loads. Lime also provides an *autogenous healing* property to mortar. Autogenous healing refers to the self-sealing of small cracks produced either within the mortar or at the interface between the mortar and the units. The cracks may result from either the bending stresses in masonry or the drying shrinkage of Portland cement in mortar.

MORTAR STRENGTH: THE ROLES OF PORTLAND CEMENT AND LIME

Two strength properties of mortar are generally of interest:

- Compressive strength
- Flexural tensile bond strength

Although several factors affect the compressive strength of mortar, the most important factor is the mortar's cementitious content. As we will observe later, the total amount of cementitious content (Portland cement plus lime) in various types of mortar is roughly constant with respect to the amount of sand. The relative proportions of Portland cement and lime are, however, different.

Increasing the amount of Portland cement with respect to lime increases the mortar's compressive strength. Conversely, increasing the amount of lime with respect to Portland cement decreases the mortar's compressive strength. Because mortar is an integral part of a masonry wall, its strength affects the compressive strength of the wall, Figure 24.2.

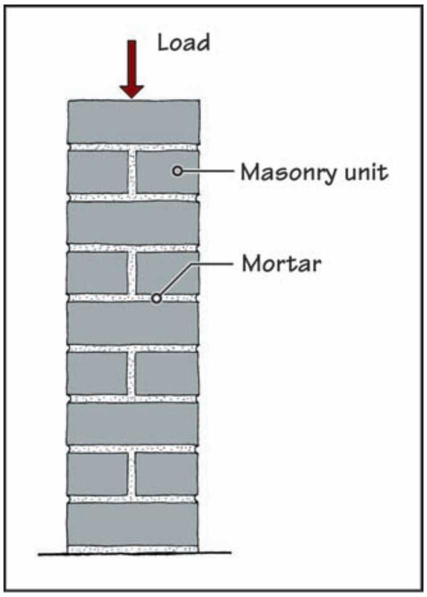


FIGURE 24.2 Because a masonry wall is composed of masonry units and mortar, the compressive strength of the wall is a function of the strength of the units and the strength of the mortar.

Unlike the compressive strength of mortar, which is a property only of the mortar, bond strength is a property of the masonry wall. It is a measure of the bond between the masonry units and the mortar. It comes into play when an unreinforced masonry wall is subjected to bending (flexure), Figure 24.3.

The bond between a masonry unit and the mortar is both a chemical and a mechanical bond. Therefore, the bond strength of masonry is a function of several factors, such as the types of units, surface roughness of units, workmanship (such as the pressure applied between the units at the time of mortaring), curing conditions (air temperature, wind, and humidity), and so on.

Another important factor that affects the bond between the mortar and the units is the amount of water in mortar. The amount of water in mortar must be sufficiently high so that the mortar can flow and be sucked into the minute crevices in masonry units. This develops and improves the bond between the units and the mortar. Everything else being the same, increasing the amount of Portland cement in mortar with respect to lime increases the bond strength of masonry.

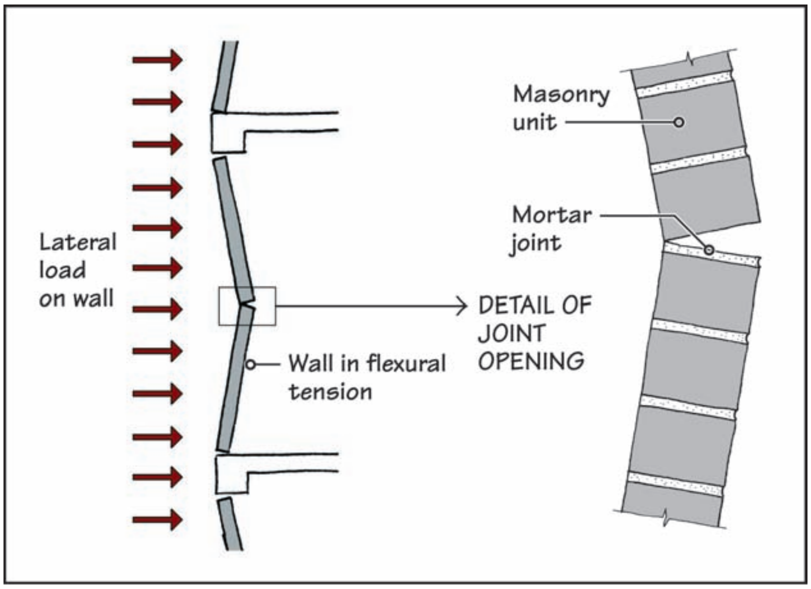


FIGURE 24.3 A wall is subjected to flexural tension when it is subjected to lateral loads (wind or earthquake). The flexural tension can lead to the wall's cracking. Because the bond between the units and the mortar is much weaker than the tensile strength of the units, the wall generally cracks at the mortar joints, that is, the mortar joints open up.

This illustration shows the opening up of horizontal mortar joints caused by the vertical bending of the wall. If the wall bends horizontally, vertical joints will tend to open.

The bond strength of masonry is pertinent primarily in an unreinforced masonry wall, such as masonry veneer, or in an unreinforced masonry backup wall. In a vertically reinforced masonry wall, Figure 24.4, steel reinforcement resists flexural tension. Therefore, from a purely structural viewpoint, the bond strength is not relevant in a reinforced masonry wall (Figure 24.4).

REQUIRED STRENGTH OF MASONRY MORTAR

The foregoing discussion indicates that the strength of a masonry wall is directly related to the strength of the mortar. It also indicates that an increase in lime (with respect to Portland cement) decreases the strength of mortar and, hence the strength of a masonry wall, but it increases the wall's watertightness.

A wall's watertightness is just as important as its strength. In fact, both watertightness and strength are somewhat interrelated. Water penetrating a wall corrodes steel reinforcement, ties, and other embedded accessories, which may ultimately reduce the wall's strength. The masonry industry, therefore, favors a relatively low-strength mortar for most masonry walls.

Another reason for choosing a low-strength mortar is to ensure that if the cracking of a masonry wall occurs, it should occur in mortar joints, not in the units, because it is much easier to repair a broken mortar bed than a broken masonry unit. Because a low-strength mortar is more workable, it provides better workmanship and full coverage of joints and, hence, a more watertight wall. In fact, a general recommendation for masonry walls is as follows:

> *Specify the weakest mortar that will give the required performance.*

NOTE

Flexural Tensile Bond Strength

A wall subjected to bending (flexure) experiences tension as well as compression. These stresses are referred to as *flexural tension* and *flexural compression*, respectively. Because unreinforced masonry is relatively stronger in compression than in tension, the *flexural tensile strength* of masonry is more critical than the *flexural compressive strength*.

Because flexural tensile strength (of an unreinforced masonry wall) is due to the bond between the units and the mortar, it is called *flexural tensile bond strength*, or simply *bond strength* (Figure 24.3). As stated in the text, bond strength is not relevant in a masonry wall provided with steel reinforcing bars to resist bending (Figure 24.4).

EXPAND YOUR KNOWLEDGE

A Historical Note on Cementitious Materials in Mortar

Before the discovery of Portland cement, masonry mortar consisted of lime (as the cementitious material) and sand. After the discovery of Portland cement, masons discarded the use of lime and made the mortar using only Portland cement and sand. The change from lime mortar to Portland cement mortar was instinctive and spontaneous because Portland cement gives a much stronger mortar than lime. Additionally, Portland cement sets and hardens far more rapidly than lime, allowing masons to lay more masonry units per day than using lime mortar, increasing the masons' productivity.

Remember from Chapter 21 that the setting and hardening of lime are due to its carbonation reaction with carbon dioxide in air. Because air contains only about 0.04% carbon dioxide, the setting and hardening of lime are slow. The setting and hardening of Portland cement, on the other hand, are due to Portland cement's reaction with water, whose quantity is generally far greater than that needed for the hydration reaction.

A few decades later, however, it was discovered that the walls made with Portland cement mortar leaked far more than those made with lime mortar. The investigation of the walls' permeability to water has led to our understanding of the importance and benefits of using lime in contemporary masonry mortar.

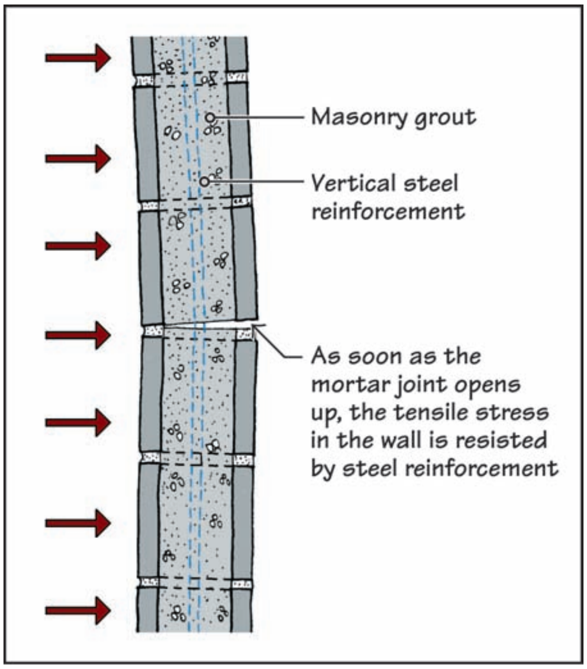

Masonry grout
Vertical steel reinforcement
As soon as the mortar joint opens up, the tensile stress in the wall is resisted by steel reinforcement

FIGURE 24.4 Flexural tensile stress in a reinforced (and grouted) masonry wall is resisted by the bond between the masonry and mortar only until the mortar joints have opened. This is the case with relatively small lateral loads. As the load increases and a mortar joint opens, the entire tensile stress is now borne by the steel reinforcement. The bond between the masonry and the mortar is now irrelevant. For a three-dimensional illustration of a (vertically) reinforced masonry wall, see Figure 25.7.

However, there are structures in which the strength of masonry is more important than its watertightness, such as the walls located in high-wind or seismic zones and heavily loaded interior walls. In these structures, a high-strength mortar is recommended.

24.2 MORTAR MATERIALS AND SPECIFICATIONS

Mortar is prepared at the construction site in a small mixer (see Figure 21.19). Hand mixing with a shovel is appropriate only for a very small job. The amount of water needed in a mortar mix is not controlled by specifications but left to the discretion of the mason to obtain the required workability. Water for mortar must be clean, potable, and free of impurities.

MATERIALS FOR MASONRY MORTAR

Portland cement used in mortar is the same as that used in making concrete (see Chapter 21). Generally, Type I/II Portland cement is used. Lime for mortar is Type S lime (see Chapter 21).

The sand used in mortar is referred to as *mason's sand*. It may be manufactured sand (pulverized stone) or mined from natural sand deposits. It must conform to ASTM specifications, which require specific grading (particle size variation). This grading gives the mason's sand nearly 30% voids within a given volume of sand. The voids are the spaces between individual sand particles, which are filled by the binder (Portland cement and lime).

PROPORTION SPECIFICATION—PORTLAND CEMENT AND LIME (PCL) MORTAR

Because the cementitious materials fill the voids between the sand particles, the total amount of cementitious compounds in a masonry mortar is almost fixed. Mortar specifications require the amount of sand in a mortar to lie between $2\frac{1}{4}$ and 3 times the amount of cementitious compounds—Portland cement + lime (PCL). The sand: PCL ratio is a volumetric ratio, not a weight ratio. In other words:

$$\frac{\text{Volume of sand}\,(\text{ft}^3)}{\text{Volume of PCL}\,(\text{ft}^3)} = 2.25 \text{ to } 3.0$$

The range allows the masons to adjust the mix for workability and water retentivity of the mortar.

Varying the relative proportions of Portland cement and lime in a mortar mix provides different types of mortar—referred to as *Types M*, *S*, *N*, and *O*, Table 24.1. Different mortar types have different recommended applications.

Mortar Type M has the maximum amount of Portland cement and hence the least amount of lime. It gives the strongest mortar. Because of its low lime content, Type M mortar is the

TABLE 24.1 TYPES OF PORTLAND CEMENT PLUS LIME (PCL) MORTARS BASED ON MATERIAL PROPORTIONS

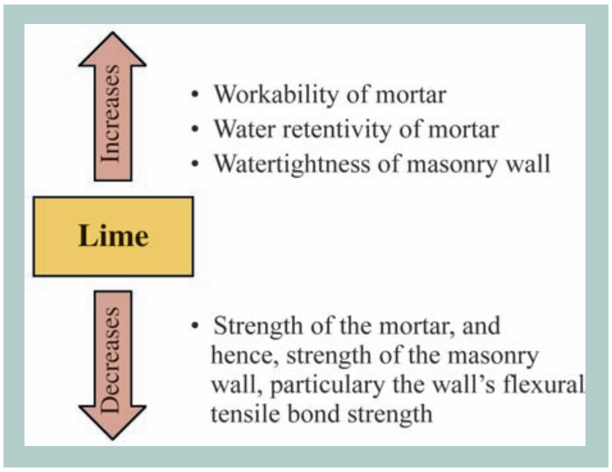
		Materials to Be Proportioned by Volume			
	Mortar type	Portland cement (PC)	Lime (L)	Sand	Recommended applications
Strongest Mortar	M	1	$\frac{1}{4}$	As per ASTM specifications, the amount of sand for all types of mortar is $2\frac{1}{4}$ to 3 times the amount of cementitious materials (PCL). Generally, however, the amount of sand used is 3 times (PCL). Thus, in Type S mortar, if PC = 1 ft^3 and L = 0.5 ft^3, the amount of sand is $3(1 + 0.5) = 4.5\ \text{ft}^3$	Interior masonry floors, foundation walls, parapet walls, and so on
	S	1	Over $\frac{1}{4}$ to $\frac{1}{2}$		Load-bearing and non-load-bearing walls in seismic or high-wind regions, chimneys, and so on
	N	1	Over $\frac{1}{2}$ to $1\frac{1}{4}$		General-purpose mortar for exterior load-bearing and non-load-bearing walls
Weakest Mortar	O	1	Over $1\frac{1}{4}$ to $2\frac{1}{2}$		Interior non-load-bearing walls in nonseismic and low-wind regions
		The amount of water should be as much as that required for workability by the mason. This recommendation is unlike that in concrete, where, for strength reasons, the minimum amount of water is recommended to produce the required workability and consistency.			

least workable, is less elastic in its hardened state, exhibits more shrinkage, and, therefore, results in a wall with greater potential for leakage. It is not recommended for use in walls, except below-grade (foundation) walls. It may be used in interior masonry floors for its greater strength and abrasion resistance. (Exterior masonry paving is generally mortarless.)

Type O mortar has the least amount of Portland cement and the maximum amount of lime, and hence is the weakest mortar. Because of its low strength (and hence low durability), Type O mortar is not generally recommended for use in contemporary exterior walls. The most common use for Type O mortar is for tuck-pointing repairs of old historic masonry.

Type S mortar is commonly recommended for exterior (load-bearing or non-load-bearing) walls in seismic or high-wind regions. It is preferred over Type N mortar because of its higher bond strength, although it is less water resistant. Type N mortar is the general-purpose mortar, used in most non-load-bearing exterior walls, such as masonry veneer walls. It may also be used in load-bearing walls. However, where greater strength and durability are needed, Type S mortar should be considered.

NOTE


Increases
Lime
Decreases
• Workability of mortar
• Water retentivity of mortar
• Watertightness of masonry wall
• Strength of the mortar, and hence, strength of the masonry wall, particulary the wall's flexural tensile bond strength

PROPORTION SPECIFICATION USING MASONRY CEMENT OR MORTAR CEMENT

Although PCL mortar is commonly used, a preblended cementitious mix for mortar (in one bag) is available. It is sold as *masonry cement* and is available as Types M, S, and N, Figure 24.5. Thus, to produce a Type S mortar, the mason simply mixes 1 ft^3 of Type S masonry mortar with 2$\frac{1}{4}$ ft^3 to 3 ft^3 of sand. There is no need to use separate Portland cement and lime bags.

The use of one-bag masonry cement precludes the need to measure and mix the cementitious materials on site, thus simplifying the preparation of mortar. It also results in a mortar that is more consistent in quality and appearance than a PCL mortar. In masonry cement, cementitious materials are factory blended under a stricter quality-control environment than a site-mixed PCL mortar.

FIGURE 24.5 A Type N masonry cement bag.

Masonry cement may contain cementitious materials other than Portland cement and may contain pulverized limestone in place of lime. To improve the workability of mortar, some manufacturers use air-entraining agents in their masonry cement. This reduces the bond between the units and the mortar. Codes recognize these facts by reducing the allowable bond strength of masonry built with masonry cement mortar.

Another preblended cementitious mix for mortar is called *mortar cement*. Like masonry cement, it is also a one-bag mix, but it differs from masonry cement in that it gives the same bond strength as PCL mortar. Masonry codes treat mortars made with mortar cement or PCL as being equivalent. Like masonry cement, mortar cement bags are available in Types M, S, and N.

PROPERTY SPECIFICATION OF MORTAR

An alternative way to specify mortar is by its properties, similar to the way concrete is specified. The most distinguishing mortar property is its compressive strength, determined by crushing 2-in. × 2-in. cubes after 28 days.

By testing the cubes, the amounts of cementitious materials can be established in the laboratory to give the required mortar strength. The proportions so established are used in producing the mortar at the construction site. The sand content in a mix obtained from property specification is generally greater than that used in the proportion specification (2$\frac{1}{4}$ to 3 times the cementitious materials).

NOTE

A Note on the Strength of Mortar

The compressive strengths of mortar given in Table 24.2 are 28-day strengths, obtained from tests of 2-in. mortar cubes prepared in the laboratory. The actual compressive strength of the corresponding mortars in the wall is much higher than the tabular values because of the small ($\frac{3}{8}$-in.) thickness of mortar and the confinement provided by the units.

EXPAND YOUR KNOWLEDGE

Letter Designations (M, S, N, and O) for Mortar Types

The letters *M*, *S*, *N*, and *O* are the alternate letters in the word *masonwork:*

MaSoNwOrK

Although the letter *K* does not represent any current ASTM mortar type, it is used in preservation work (as a more appropriate substitute for Type O mortar) to simulate historic masonry, where only lime mortars were used. Type K mortar has 1 part Portland cement and 2$\frac{1}{2}$ to 4 parts lime.

Types M, S, N, and O have been preferred over Types I, II, III, and IV (or Types 1, 2, 3, and 4) because no type is better than the other. Each type has its own unique set of applications.

TABLE 24.2 STRENGTHS OF MORTAR TYPES BASED ON PROPERTY SPECIFICATIONS

Mortar type	Compressive strength (psi)
M	2,500
S	1,800
N	750
O	350

Mortar produced in the laboratory using the property specification is referred to as *Type M* mortar if its 28-day compressive strength is at least 2,500 psi, as *Type S* mortar if its compressive strength is at least 1,800 psi, and so on, as shown in Table 24.2.

PROPERTY SPECIFICATION VERSUS PROPORTION SPECIFICATION OF MORTAR

The use of the property specification in place of the proportion specification leads to greater economy in the use of cementitious materials. In other words, a mortar type based on proportion specification generally has greater strength than that given in Table 24.2, but it also uses a greater amount of cementitious materials.

Because the property specification requires laboratory preconstruction testing, it is more cumbersome to follow and enforce. Therefore, the use of property specification is relatively uncommon. It is generally used in situations where a unique mortar type is needed or where the available materials do not meet the required specifications (e.g., sand does not meet gradation requirements).

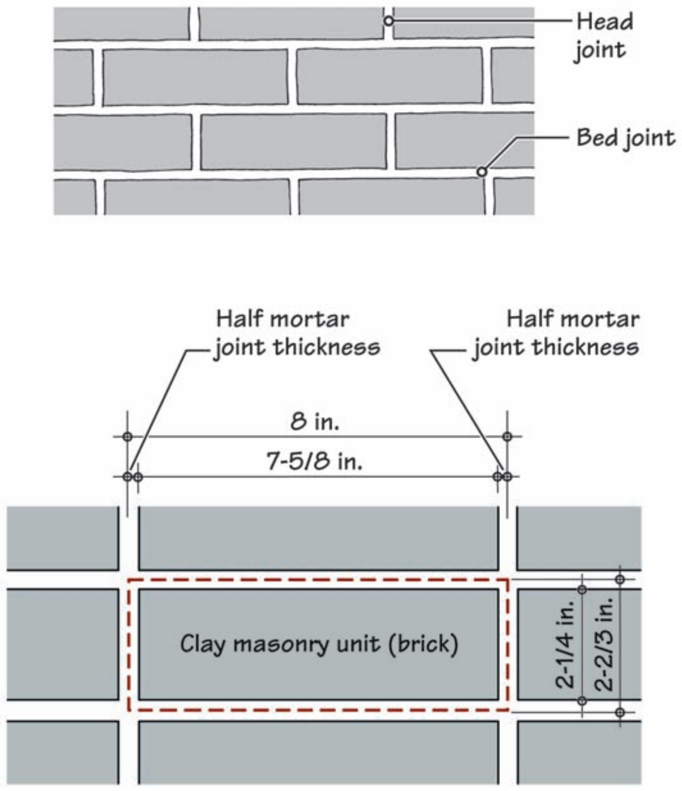
The specifier must use only one type of specification, either property specification or proportion specification, not both for a project. If neither is specified, the proportion specification governs by default.

WHITE AND COLORED MORTARS

In a typical brick masonry wall (in running bond, see Section 24.7), mortar occupies nearly 20% of the wall's facade area; the remaining 80% is occupied by the bricks, Figure 24.6. Therefore, the color of mortar and the profile of mortar joints contribute greatly to the aesthetics of a masonry wall.

White mortar joints against dark-colored masonry units provide handsome contrast. White mortar against white or light-colored units gives pleasant harmony. White mortar is obtained by using white Portland cement and white sand. White masonry cement is also available, Figure 24.7.

Color pigments can also be added to a mortar mix to produce a colored mortar. In colored mortar, white Portland cement (or white masonry cement) and white sand are generally used to provide greater control of mortar color.


Head joint
Bed joint
Half mortar joint thickness
Half mortar joint thickness
8 in.
7-5/8 in.
Clay masonry unit (brick)
2-1/4 in.
2-2/3 in.

Area of brick surface = 7-5/8 × 2-1/4 = 17.2 in.^{2}
Area of brick and mortar surface = 8 × 2-2/3 = 21.3 in.^{2}
Area of mortar = Difference between above areas = 4.1 in.^{2}
Percentage mortar area = (4.1/21.3)100 = 19.2%, or say 20%

FIGURE 24.6 In a typical (modular) brick wall, mortar occupies nearly 20% of the wall's elevation, as shown by the calculations. The red dashed lines represent the center lines of the mortar joints around one brick unit.

WHITE MASONRY CEMENT
TYPE N

FIGURE 24.7 A Type N white masonry cement bag.

PRACTICE **QUIZ**

Each question has only one correct answer. Select the choice that best answers the question.

1. The term CMU is generally used as an acronym for
  - **a.** clay masonry unit.
  - **b.** concrete masonry unit.
  - **c.** clay masonry underbed.
  - **d.** concrete masonry underbed.
  - **e.** cement mortar underbed.

2. The cementitious material(s) in contemporary masonry mortar consist(s) of
  - **a.** Portland cement.
  - **b.** lime.
  - **c.** Portland cement and sand.
  - **d.** Portland cement and lime.
  - **e.** Portland cement, lime, and sand.

3. Which of the following materials increases the mortar's cohesiveness?
  - **a.** Mortar joint profile
  - **b.** Portland cement
  - **c.** Sand
  - **d.** Lime
  - **e.** All of the above

4. Which of the following materials increases the mortar's compressive strength?
  - **a.** Mortar joint profile
  - **b.** Portland cement
  - **c.** Sand
  - **d.** Lime
  - **e.** All of the above

5. Which of the following materials increases the mortar's workability?
  - **a.** Mortar joint profile
  - **b.** Portland cement
  - **c.** Sand
  - **d.** Lime
  - **e.** All of the above

6. A wall made of Portland cement mortar (without lime) is more watertight than a wall made of Portland cement and lime mortar.
  - **a.** True
  - **b.** False

7. The flexural tensile bond strength of a masonry wall is relevant in
  - **a.** an unreinforced masonry wall subjected to gravity loads.
  - **b.** an unreinforced masonry wall subjected to lateral loads.
  - **c.** a reinforced masonry wall subjected to gravity loads.
  - **d.** a reinforced masonry wall subjected to lateral loads.
  - **e.** all of the above.

8. The flexural tensile bond strength of a masonry wall is a function of
  - **a.** the compressive strength of mortar.
  - **b.** the type of masonry units.
  - **c.** the quality of workmanship.
  - **d.** the curing of mortar.
  - **e.** all of the above.

9. For a masonry wall, the compressive strength of mortar should be as high as economically feasible.
  - **a.** True
  - **b.** False

10. Masonry mortar types are classified as
  - **a.** Types M, S, N, and O.
  - **b.** Types I, II, III, and IV.
  - **c.** Types 1, 2, 3, and 4.
  - **d.** Types P, Q, R, and S.
  - **e.** either (b) or (c).

11. The mortar with the highest compressive strength is
  - **a.** Type M.
  - **b.** Type I.
  - **c.** Type 1.
  - **d.** Type P.

12. The mortar most commonly used in an exterior masonry veneer wall is
  - **a.** Type S.
  - **b.** Type N.
  - **c.** Type I.
  - **d.** Type II.
  - **e.** Type P.

13. The mortar commonly recommended for use in masonry walls in seismic regions is
  - **a.** Type I.
  - **b.** Type II.
  - **c.** Type P.
  - **d.** Type S.
  - **e.** Type N.

14. Mortar may be specified either by proportion specification or by property specification. Which of these two is more commonly used?
  - **a.** Proportion specification
  - **b.** Property specification

15. When mortar is specified using proportion specification, various solid materials that constitute masonry mortar are proportioned based on their
  - **a.** wet weights.
  - **b.** dry weights.
  - **c.** wet volumes.
  - **d.** dry volumes.
  - **e.** none of the above.

16. A preblended cementitious mix for masonry mortar is available as
  - **a.** PCL cement.
  - **b.** masonry cement.
  - **c.** mortar cement.
  - **d.** (a) and (b).
  - **e.** (b) and (c).

24.3 MORTAR JOINT THICKNESS AND PROFILES

A masonry wall consists of horizontal and vertical mortar joints, referred to as *bed joints* and *head joints*, respectively (Figure 24.6). For aesthetic and practical reasons, both joints are generally of the same thickness.

The most commonly used mortar joint thickness is $\frac{3}{8}$ in. This thickness has been established after considering several factors, including the embedment of joint reinforcement in mortar. The mortar's ability to provide a cushion between the units and to absorb their dimensional variations implies that the mortar joints cannot be too thin.

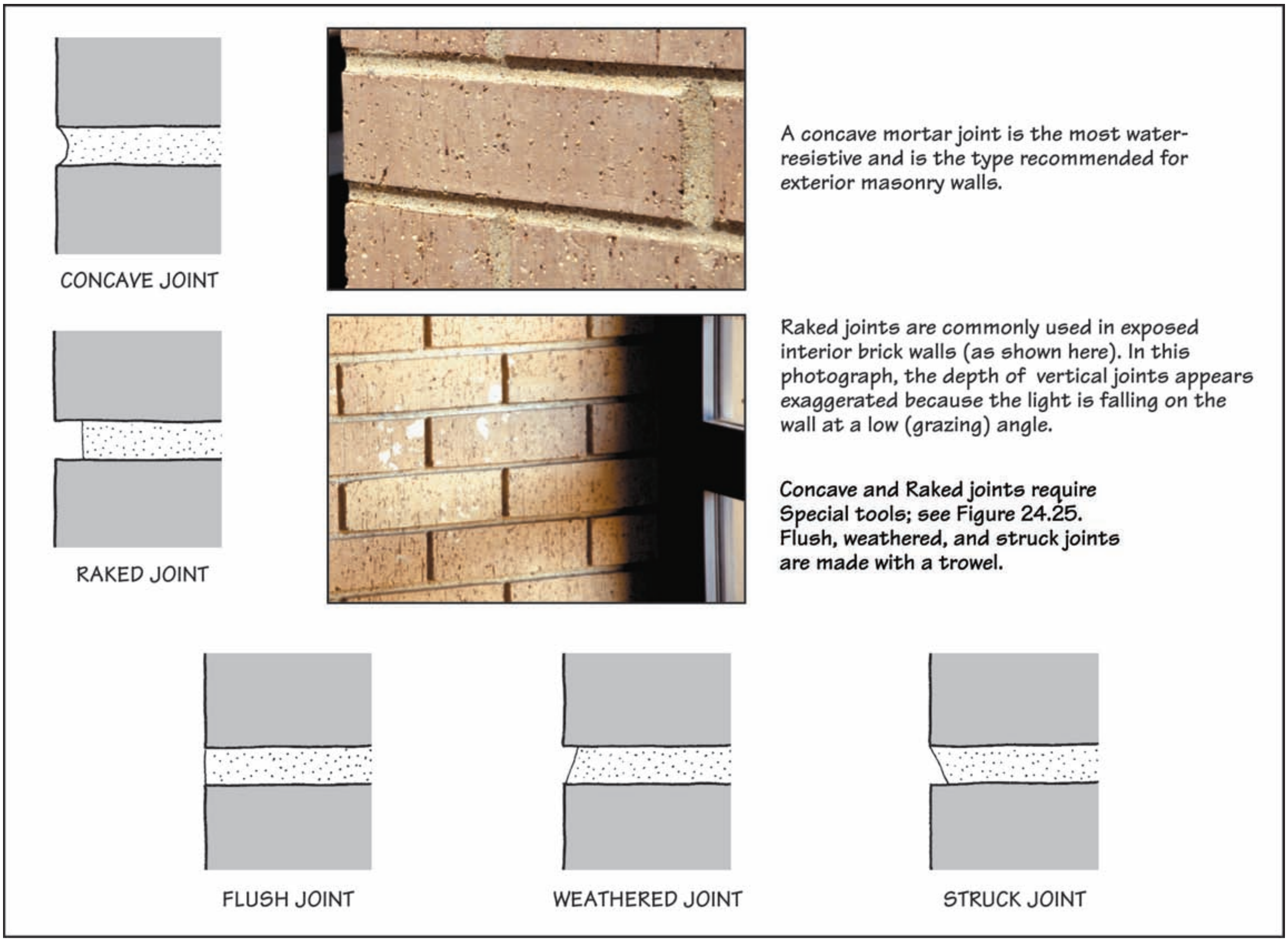
NOTE

The diameter of wire used as joint reinforcement is limited to a maximum of half the mortar joint thickness, that is, to a diameter of $\frac{3}{16}$ in. in a $\frac{3}{8}$-in-thick mortar joint. See Section 25.4 for a description of joint reinforcement.

MORTAR JOINT PROFILES

The mortar joint profile affects not only the aesthetics of the wall, but also the water resistance of the wall. Some commonly used mortar joint profiles, as shown in Figure 24.8, are

- Concave joint
- Raked joint
- Flush joint
- Weathered joint
- Struck joint



A concave mortar joint is the most water-resistive and is the type recommended for exterior masonry walls.

Raked joints are commonly used in exposed interior brick walls (as shown here). In this photograph, the depth of vertical joints appears exaggerated because the light is falling on the wall at a low (grazing) angle.

Concave and Raked joints require Special tools; see Figure 24.25. Flush, weathered, and struck joints are made with a trowel.

FIGURE 24.8 Commonly used mortar joint profiles.

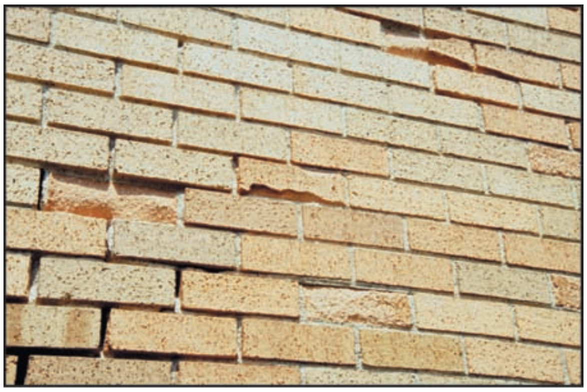


FIGURE 24.9 Spalling of bricks due to freeze-thaw action. In freeze-thaw action, the water absorbed by a wall expands on freezing, producing compressive stresses in the wall. Over repeated freeze-thaw cycles, a wall (made of a low-strength material) spalls, that is, crumbles and falls off.

The most watertight joint profile is the concave joint. It is obtained by tooling the joint with a cylindrical tool that compresses the mortar against itself and the units (Figure 24.25). Because most water penetrates a masonry wall through the unit-to-mortar interface (relatively little penetrates through the units or the mortar), compressing the mortar improves the seal between the units and the mortar. A concave joint is also more resistant to freeze-thaw damage, Figure 24.9.

The compression and the resulting seal provided by a concave joint are not provided by other joint profiles. That is why a tooled concave joint profile is generally recommended for all exterior masonry.

For interior masonry, raked joints and flush joints are common. Raked joints highlight the units by providing deeper shadows within the mortar. This effect is dramatized if the light falls at a low angle to the wall. The disadvantage of raked joints is that they collect dust. Flush joints are used for interior masonry where dust is a concern. Between weathered and struck joints, the weathered joint gives greater water resistance by directing the water away from the joint.

24.4 MANUFACTURE OF BRICKS

In North America, brick (clay) masonry is generally used either as an exterior or an interior wall cladding material, for example, brick veneer (see Chapter 28). The high strength of bricks makes them durable against freezing and thawing and against slow erosion by rainwater and wind—important requirements for an exterior finish. Several brick manufacturers make their bricks with a compressive strength of 6,000 psi to 10,000 psi. Clay masonry is also suitable as an exterior cladding due to its mass, which provides high fire resistance and sound-insulating properties (see Chapter 8). Finally, constructing a brick wall requires a high level of craft. This gives brick facades an aesthetic character not available in other facade materials, such as site-cast concrete, precast concrete, or insulated metal panels.

The appearance of a brick facade conveys an image of permanence and stability; brick facades are used frequently in significant civic buildings, schools, and college campuses. In fact, as a facade material, brick is by far the most widely used material in contemporary buildings.

The high strength of bricks should make them a logical choice for load-bearing wall applications. However, this is not the case. The reason is that it is more difficult to insulate a brick wall or reinforce it with steel bars than a concrete masonry wall. Therefore, in load-bearing masonry construction, the load-bearing component is generally concrete masonry, with brick as a facade material (see Chapter 28).

BRICK MANUFACTURING

The primary raw materials for making bricks are clay and shale. The two main constituents of clay and shale are the oxides of silicon and aluminum. Some minor components are iron and other metal oxides, which are particularly responsible for giving brick its red-brown color. White and light-colored bricks are made by using clay that is naturally deficient in metal oxides and removing whatever metal oxides are present in it. White bricks are generally more expensive than the normal (red-brown) bricks.

Although modern technology has substantially changed the details of brick manufacturing, it is conceptually simple and consists of the following six operations:

- Mining clay from the ground
- Grinding and sieving clay to a fine powder
- Mixing water with sieved clay
- Forming wet clay into the desired brick shape (green bricks)
- Drying green bricks
- Firing dried bricks in a kiln

Brick shapes can be formed by one of the following two methods:

- Extrusion of wet clay through a die—*extruded bricks*
- Molding wet clay—*molded bricks*

NOTE

Difference Between Clay and Shale

Clay is available at the surface of the earth. Therefore, clay and *surface clay* are synonymous terms. *Shale* is also clay, but it is available deep in the ground. Because of the pressure of the overlying material, shale has hardened to a high compressive strength, almost equaling that of stone.

EXTRUDED BRICKS

The extrusion of wet clay is done by forcing it through a die, which yields a column of clay that slides over a moving belt, Figure 24.10. The process is similar to the extrusion of toothpaste through a tube. The die consists of conical rods, which create *core holes* in the clay column. The cross-sectional dimensions of the clay column determine the length and width of the brick.

As the clay column moves forward, a wire cutter, consisting of a number of parallel wires, cuts it into individual bricks, Figure 24.11. The spacing between wires is the brick

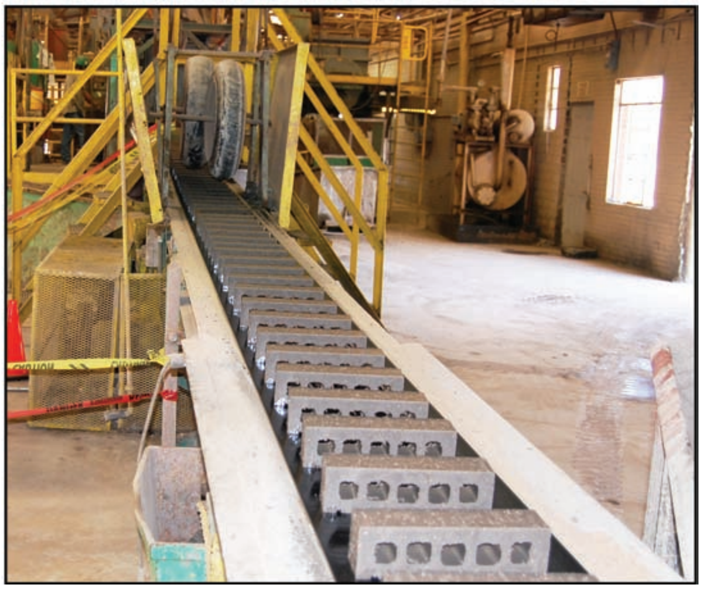


FIGURE 24.10 Manufacture of extruded (clay) bricks. A wet clay column emerging from the die with core holes. The die contains a number of conical steel rods (in this case, five rods) that form the core holes. As the wet column advances over the rollers, it is wire cut into individual bricks. (See also Figure 24.11.)

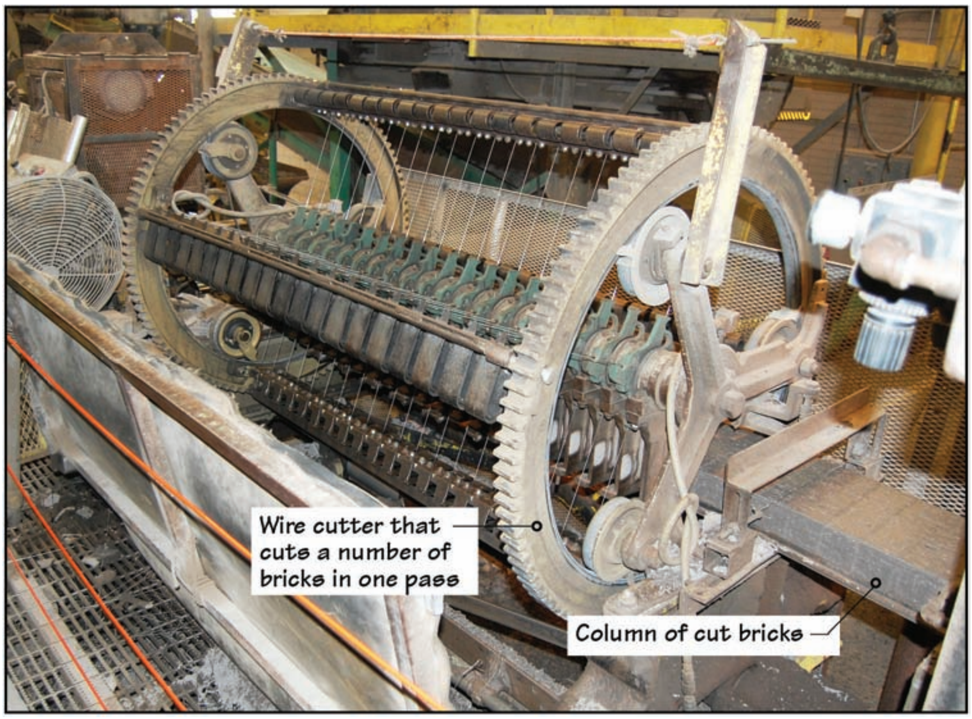


FIGURE 24.11 An automatic rotary wire cutter that cuts the wet clay column into several bricks in one pass.

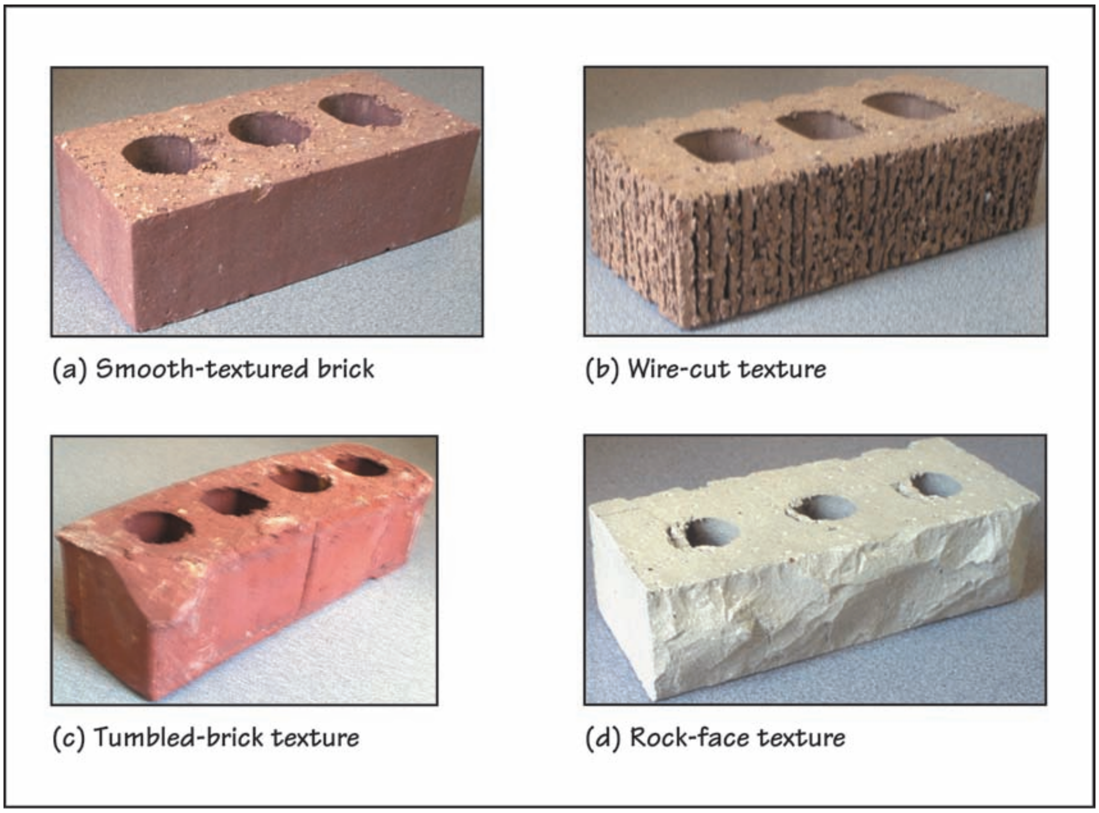


FIGURE 24.12 A few of the several textures available on extruded bricks.

height. If any surface texture is to be applied to bricks, it is applied before the cutting operation. If no surface texture is applied, the brick has a smooth surface finish resulting from the pressure applied by the steel die as the clay passes through it. That is why the smooth texture is referred to as *die skin texture*. A few commonly used surface textures are shown in Figure 24.12.

After the bricks have been cut, they are transported to a drying chamber, in which the temperature ranges from 100°F (38°C) to 400°F (150°C). Bricks must be dried before being fired in the kiln to prevent cracking of green bricks. The heat used in the drying chamber is the exhaust heat from the kiln where the bricks are fired.

The kiln used in modern brick manufacturing plants is a long, tunnel kiln, Figure 24.13. Cars of dried bricks move slowly through the kiln on a rail. The kiln temperature varies from nearly 400°F at the entry point of the dried bricks to a maximum of about 2,000°F (1,100°C). At nearly 2,000°F (1,100°C), clay particles soften (virtually melt) and fuse together, creating a hard, strong brick. Fired bricks are removed from the kiln, sorted, strapped in cubes, and stored in the yard until delivery to the construction site, Figure 24.14.

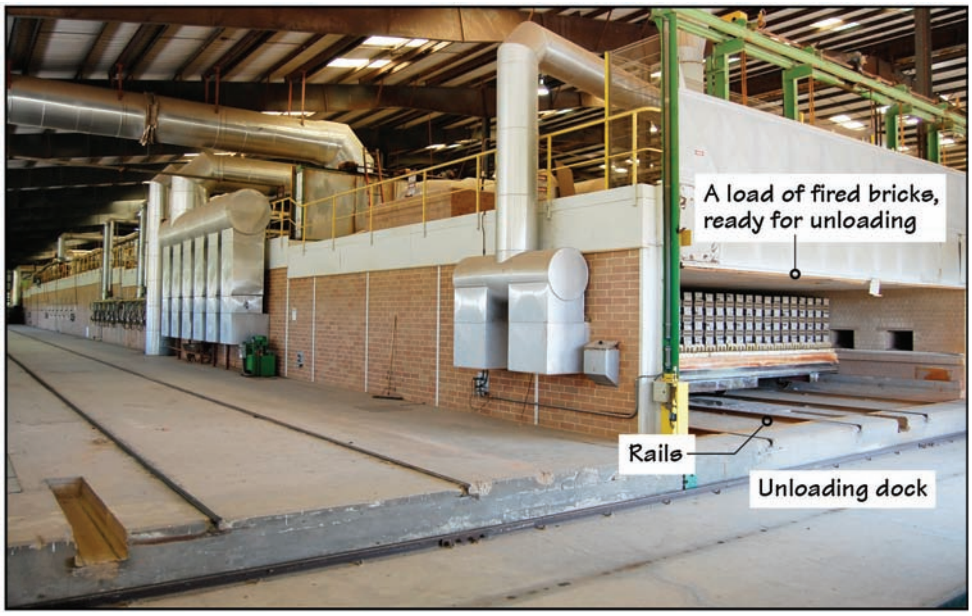
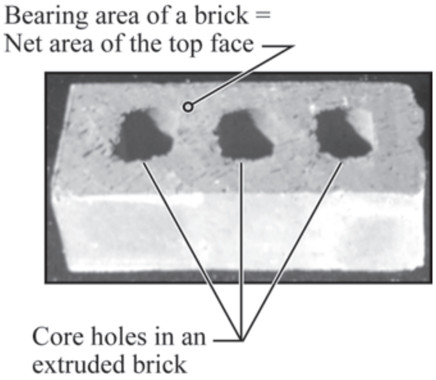


FIGURE 24.13 A typical tunnel kiln in which the air-dried bricks are fed from one end (in this case, the left-side end), travel through the kiln on rails at controlled speed, and the fired bricks are unloaded for storage in the brick manufacturing yard for shipment, shown in Figure 24.14.

FIGURE 24.14 A typical storage yard at a brick manufacturing plant.

CORE HOLES IN EXTRUDED BRICKS


Bearing area of a brick = Net area of the top face
Core holes in an extruded brick

Extruded bricks have through-and-through core holes. The primary reason for core holes is that they lead to more uniform drying and firing of bricks. Although the core holes reduce the bearing area of a brick and, hence, the compressive strength of masonry, the improved unit strength resulting from uniform firing compensates for the bearing area reduction. Core holes also improve the bond between the bricks and the mortar. The number and sizes of core holes are manufacturer specific, depending on the size of the brick.

MOLDED BRICKS AND FROGS

Molded bricks are made by force dropping individual lumps of wet clay into brick molds. The excess clay is scraped off the molds, and green bricks are removed from the mold immediately thereafter. Modern brick manufacturing is highly mechanized, and several bricks can be molded in one single pass rather than by the historic molding of individual bricks. In both extruded and molded-brick manufacturing, there is little, if any, manual handling.

Because the clay-water mix is pushed under pressure through a die for extruded bricks, it is a fairly stiff mix. By contrast, the clay-water mix for molded bricks must contain more water. As the water evaporates, it leaves voids in bricks. Consequently, a molded brick is generally weaker and softer than an extruded brick. However, molded bricks are preferred by some designers and owners because they do not have the machine-like (more precise) appearance of extruded bricks.

Whereas an extruded brick has through-and-through core holes, a molded brick contains a depression, referred to as a *frog*. The frog can take many shapes, depending on the manufacturer. Two such frogs are shown in Figure 24.15. In laying the molded bricks in a wall, the frog faces downward, so that any water entering the wall will not be held by the frog recess.

24.5 DIMENSIONS OF MASONRY UNITS

A masonry unit (both clay brick and concrete block) has three types of dimensions:

- Specified dimensions
- Nominal dimensions
- Actual dimensions

The *specified dimension* of a masonry unit is the finished dimension that the specifier has requested and the manufacturer desires to achieve. However, because the manufacturing process is not perfect, the *actual dimensions* of a unit are different from the specified dimensions. The difference between the specified and actual dimensions of a masonry unit must lie within the *dimensional tolerance* established by the industry for that product.

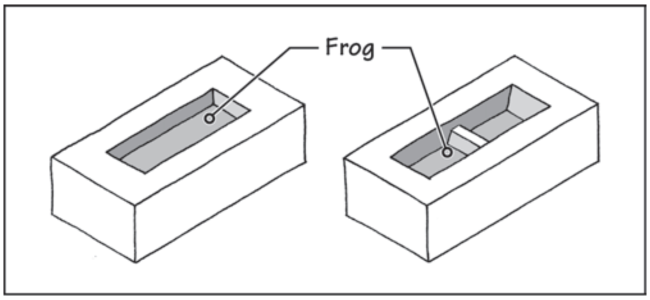


FIGURE 24.15 Two of the several shapes of frogs used in molded bricks.

A typical molded brick.

The *nominal dimension* of a unit is the specified dimension plus one mortar joint thickness. The nominal dimensions of a unit refers to the space occupied by one unit (and the associated mortar) in the wall. Thus,

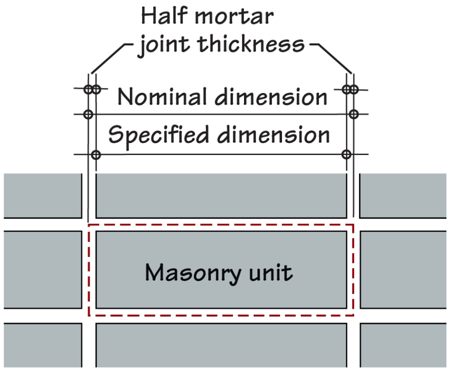
Nominal dimension = specified dimension + one mortar joint dimension

Because the standard mortar joint thickness is $\frac{3}{8}$ in., the nominal dimension of a masonry unit is $\frac{3}{8}$ in. greater than the specified dimension. Thus, if the specified length of a masonry unit is $7\frac{5}{8}$ in., its nominal length is 8 in.

In practice, the nominal dimensions of units are generally given, and the inch labels are not used. Inch marks are used with the specified dimensions. Thus, if:

A unit's nominal dimensions = $4 \times 2\frac{2}{3} \times 8$

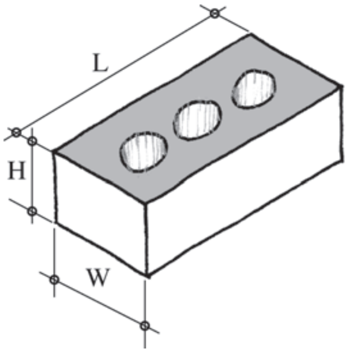
Its specified dimensions = $3\frac{5}{8}$ in. × $2\frac{1}{4}$ in. × $7\frac{5}{8}$ in.



Difference between the specified and nominal dimensions of a masonry unit. The red dashed lines represent the center lines of mortar joints.

SEQUENCING MASONRY UNIT DIMENSIONS

Observe the sequence in which the unit's dimensions have been stated. The width (W, i.e., *through-the-wall* dimension) is stated first, followed by the face dimensions—height (H) × length (L). Specifying the unit's dimensions using a sequence other than W × H × L may confuse the subcontractor, manufacturer, or supplier.



Masonry unit dimensions must be stated in the following sequence: W × H × L.

HOLLOW VERSUS SOLID MASONRY UNITS

Both bricks and concrete blocks generally contain voids. In the masonry industry, a *solid* masonry unit is less than 25% hollow (≥75% solid cross-sectional bearing area). A *hollow* masonry unit is 25% or more hollow.

Most bricks are solid units because their total core area is less than 25%. A brick without cores must be specified as *100% solid.* A 100% solid brick is generally used for paving or as coping at the top of walls. Because brick-manufacturing machinery is set up to make cored or frogged bricks, 100% solid bricks are special bricks.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

17. The most commonly used mortar joint thickness is
  a. $\frac{3}{4}$ in. **b.** $\frac{5}{8}$ in.
  c. $\frac{1}{2}$ in. **d.** $\frac{3}{8}$ in.
  e. $\frac{1}{4}$ in.

18. Which of the following mortar joint profiles should be specified for an exterior wall?
  a. Concave joint **b.** Raked joint
  c. Flush joint **d.** Weathered joint
  e. Struck joint

19. Bricks that have core holes are
  a. extruded bricks. **b.** molded bricks.
  c. (a) and (b).

20. Bricks that have frogs are
  a. extruded bricks. **b.** molded bricks.
  c. (a) and (b).

21. The primary reason for providing core holes in bricks is to
  a. reduce the weight of bricks.
  b. provide uniform drying and firing of bricks.
  c. increase the shear resistance of masonry walls.
  d. none of the above.

22. The nominal dimension of a masonry unit whose actual dimension equals $7\frac{5}{8}$ in. is
a. 7 in.
b. $7\frac{1}{4}$ in.
c. $7\frac{1}{2}$ in.
d. $7\frac{3}{4}$ in.
e. none of the above.

23. A masonry unit that has no voids (e.g., no core holes) is referred to as a
a. solid unit.
b. 100% solid unit.
c. (a) or (b).

24. A masonry unit that has 20% voids (e.g., 20% core hole area) is referred to as a
a. solid unit.
b. hollow unit.
c. partially hollow unit.
d. none of the above.

25. In specifying the dimensions of a masonry unit, which dimension is stated first?
a. Length, L, of the unit
b. Height, H, of the unit
c. Width, W, of the unit

26. In specifying the dimensions of a masonry unit, which dimension is stated last?
a. Length, L, of the unit
b. Height, H, of the unit
c. Width, W, of the unit

24.6 TYPES OF CLAY BRICKS

Bricks are available in various sizes. The most commonly used brick is the (extruded) *modular brick*, which measures $3\frac{5}{8}$ in. × $2\frac{1}{4}$ in. × $7\frac{5}{8}$ in. Its nominal dimensions are 4 × $2\frac{2}{3}$ × 8. Some of the other commonly used brick sizes are shown in Figure 24.16.

TYPES OF CLAY BRICKS BASED ON USE

Bricks used in different applications must obviously be different. The bricks used as face veneer must have lower dimensional tolerances and be more weather resistant than the bricks used in backup brick walls. Similarly, the bricks used in paving and flooring must be more abrasion resistant than facing bricks or backup bricks. Some of the commonly specified brick types are as follows:

- Facing bricks—solid or hollow
- Building bricks—solid or hollow
- Paving bricks—100% solid

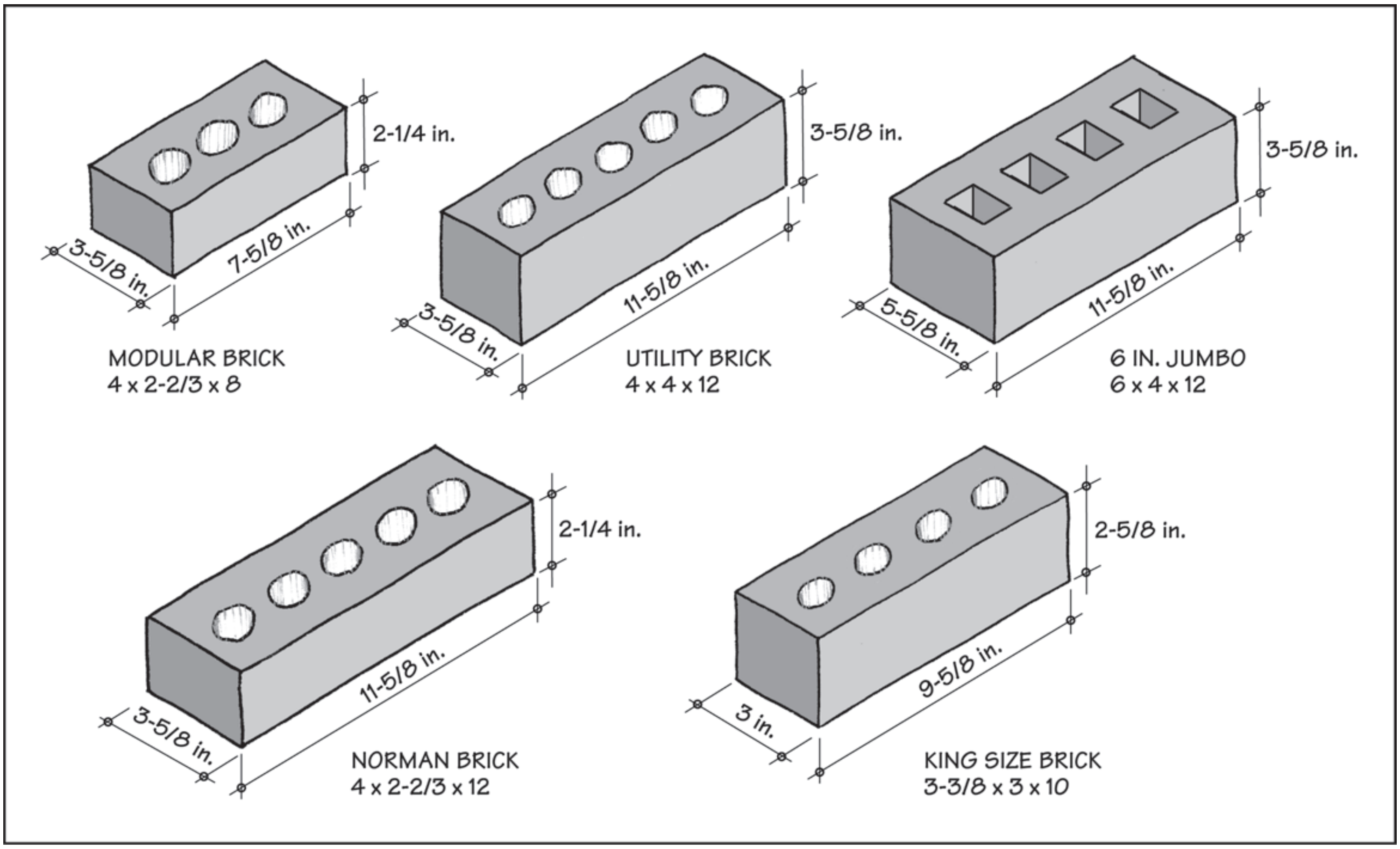

2-1/4 in.
3-5/8 in.
7-5/8 in.
MODULAR BRICK
4 x 2-2/3 x 8
3-5/8 in.
3-5/8 in.
11-5/8 in.
UTILITY BRICK
4 x 4 x 12
3-5/8 in.
5-5/8 in.
11-5/8 in.
6 IN. JUMBO
6 x 4 x 12
2-1/4 in.
3-5/8 in.
11-5/8 in.
NORMAN BRICK
4 x 2-2/3 x 12
2-5/8 in.
3 in.
9-5/8 in.
KING SIZE BRICK
3-3/8 x 3 x 10

FIGURE 24.16 Commonly used brick types.

Because clay masonry units are generally used in face veneers, the use of facing bricks is among the most common, followed by paving bricks and building bricks. We discuss these three types here. Information about other types may be obtained from applicable ASTM standards.

FACING BRICKS

Facing bricks are used in exposed exterior or interior walls and are classified as follows:

- *Type FBS*, in which the dimensional tolerances, chippage, and warpage are *standard* for the industry (hence the letter *S* in the type designation). Type FBS is the default specification for facing bricks. In other words, where no type is specified, Type FBS is provided.
- *Type FBX*, in which the lowest dimensional tolerances, chippage, and warpage are permitted. In other words, the dimensional tolerances in Type FBX are smaller than those permitted in Type FBS. The letter *X* in the type designation stands for *extra* special.
- *Type FBA*, which is specially manufactured with large variations in dimensions, textural effects, and warpage to produce architectural facing bricks (hence the letter *A* in the type designation).

NOTE

ASTM and Facing Brick

The most frequently referenced standard for facing bricks is ASTM C216, "Standard Specification for Facing Brick".

All facing bricks must meet the durability requirements of the location. The durability of facing bricks is represented by their grade, which may either be:

- Grade SW or Grade MW

Thus, an FBS (or FBX or FBA) brick can either be of Grade SW or MW. Grade SW bricks can withstand severe weathering conditions, and Grade MW bricks can withstand medium weathering conditions. Table 24.3 gives the durability requirements for brick grades. The durability of a brick refers to its freeze-thaw resistance, which is a function of the compressive strength of brick and the amount of (cold and boiling) water absorbed by the brick.

NOTE

ASTM and Building Bricks

The most frequently referenced standard for building bricks is ASTM C62, "Standard Specification for Building Brick".

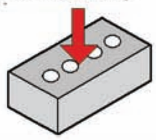
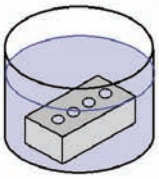
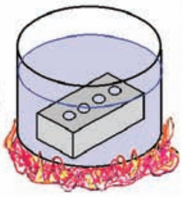
The selection of a particular grade is based on the ability of the brick to resist damage caused by freeze-thaw cycling when it is wet. One method used to assess the freeze-thaw exposure that a brick will experience is to use the weathering index (WI) of the location and the position of the brick in the building, Figure 24.17. WI is an estimate of the freeze-thaw potential of the geographic location.

If WI $\geq$ 500, the location has a *severe* freeze-thaw potential. If WI lies between 50 and 500, the location has *medium* freeze-thaw potential. If WI $<$ 50, the location has *negligible* freeze-thaw potential. Most brick manufacturers make only SW bricks to give their product the versatility of use in any climate and any position in a building.

BUILDING BRICKS

Building bricks are similar to facing bricks except that they do not have any limitations on dimensional variations, warpage, or chippage. Thus, building bricks are rated for durability

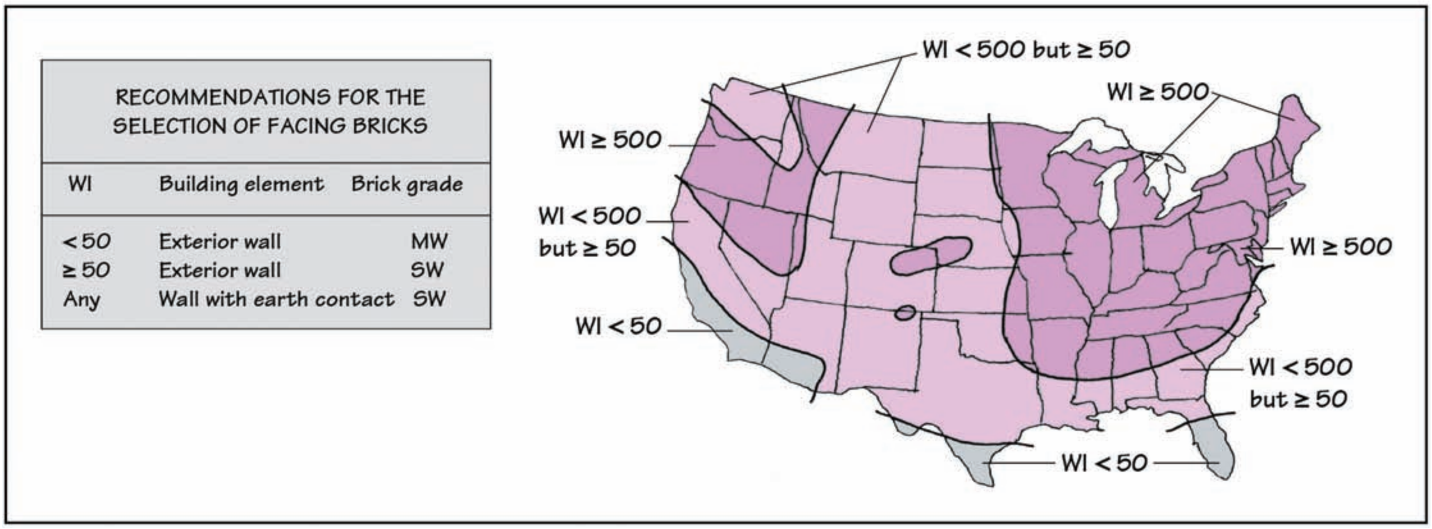
TABLE 24.3 DURABILITY REQUIREMENTS FOR VARIOUS GRADES OF BRICKS

Grade of brick	Compressive strength, S, of brick (in psi) based on its gross area (brick flatwise) 		Cold and boiling water absorption of brick  Dry brick is weighed first. Let weight of dry brick = W_1. It is then immersed in cold water for 24 hours and weighed again. Let the wet weight of brick = W_2.  The same brick is then boiled for 5 hours and subsequently weighed. Let the weight of boiled brick = W_3.				
	Minimum value of S		**Maximum value of D**		**Maximum value of SC**		C = Cold water absorption = $(W_2 - W_1)$ B = boiling water absorption = $(W_3 - W\ )$ SC = Saturation coefficient = (C/B) D = Percentage boiling water absorbed = $[(W_3 - W_1)/W_1] \times 100$
	Average of 5 bricks	**Individual brick**	**Average of 5 bricks**	**Individual brick**	**Average of 5 bricks**	**Individual brick**	
SW	3,000	2,500	17.0	20.0	0.78	0.80	
MW	2,500	2,200	22.0	25.0	0.88	0.90	
NW	1,500	1,250	No limit	No limit	No limit	No limit	

Notes: (1) All three grades apply to building bricks. Facing bricks are made to conform to SW and MW grades only. (2) Some bricks are durable but may not satisfy the requirements of this table (see the following reference).
Reference: Brick Industry Association (BIA) Technical Note 9(A): "Specifications for and Classification of Brick".

and strength only; that is, they carry a grade—Grade SW, MW, or NW. The specifications for Grade SW and MW in both facing bricks and building bricks are identical. Building bricks have an additional grade NW (Table 24.3).

Building bricks are generally used in brick walls that are covered with another facing material. However, they may be used in face veneers if their warpage, chippage, and dimensional variations are acceptable.



RECOMMENDATIONS FOR THE SELECTION OF FACING BRICKS

WI	Building element	Brick grade
< 50	Exterior wall	MW
≥ 50	Exterior wall	SW
Any	Wall with earth contact	SW

FIGURE 24.17 Weathering index (WI) map of the United States.

EXPAND YOUR KNOWLEDGE

Boiling Water Absorption, Saturation Coefficient (SC), and Freeze-Thaw Resistance

To determine the saturation coefficient of a brick, we first immerse it in cold, that is, room-temperature, water for 24 h. The amount of water absorbed by the brick in 24 h is measured. We then boil the same brick for 5 h and determine the amount of water absorbed by it. The ratio of cold-water absorption (C) to boiling-water absorption (B) is defined as the saturation coefficient (SC) of the brick; that is, $SC = C/B$. Because the brick generally absorbs more water on boiling, $B \geq C$, that is, $SC \leq 1.0$.

For example, assume that a dry brick weighs 4.5 lb, which after 24-h immersion in cold water weighs 5.0 lb. Therefore, $C = 5.0 - 4.5 = 0.5$ lb. Assume further that when the same brick is boiled for 5 h and weighed thereafter, it weighs 5.2 lb, giving $B = 5.2 - 4.5 = 0.7$ lb. The SC of brick is:

$$SC = \frac{C}{B} = \frac{0.5}{0.7} = 0.71$$

The greater the difference between the two absorptions (i.e., the smaller the SC), the greater the ability of the brick to allow the absorbed water to expand within the brick on freezing.

Although not perfect, the boiling-water absorption, the SC, and the compressive strength of a brick are the best-known measures at the present time of a brick's freeze-thaw resistance.

EXPAND YOUR KNOWLEDGE

Weathering Index of a Location

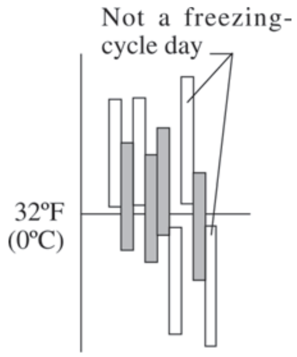
The weathering index (WI) of a location is a measure of the freeze-thaw severity of a location and is defined as:

$$\begin{aligned} \text{WI} = {} & \text{(average annual freezing-cycle days)} \\ & \times \text{(average annual winter rainfall)} \end{aligned}$$

Thus, if the number of annual freezing-cycle days for a location is 24 and the total annual winter rainfall for that location is 20 in., $\text{WI} = 24(20) = 480$.

A *freezing-cycle day* is defined as a day on which freezing and thawing occur. In other words, a freezing-cycle day is a day when the air temperature passes through 32°F (0°C). It is not necessary to examine the maximum and minimum temperatures of each day of the year to determine the number of freezing-cycle days of a location. Instead, the number of freezing-cycle days can be obtained by (number of days when the minimum temperature ≤32°F) − (number of days when the maximum temperature ≤32°F). See the adjacent sketch.

Annual winter rainfall is the total rainfall (in inches) between the first killing frost in the fall and the last killing frost in the spring.



Each bar represents the air temperature range of one day. The freezing-cycle days are highlighted.

In this sketch, the number of days when the minimum temperature ≤32°F (0°C) = 6. The number of days when the maximum temperature ≤32°F (0°C) = 2. Thus, the freezing-cycle days = 6 – 2 = 4.

NOTE

ASTM and Paving Bricks

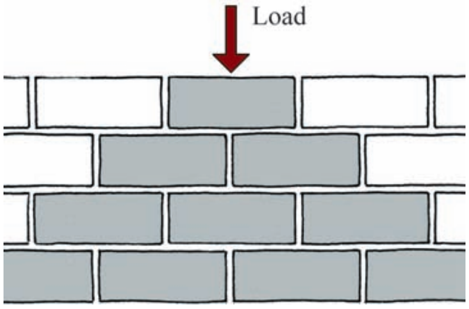
The most frequently referenced standard for paving bricks is ASTM C902, “Specification for Pedestrian and Light Traffic Paving Bricks”, or ASTM C1272, “Specification for Heavy Vehicular Paving Bricks”.

PAVING BRICKS

Paving bricks are graded for freeze-thaw as Class SX, MX, or NX—from most freeze-thaw resistant to least freeze-thaw resistant. They are also graded for abrasion resistance as Types I, II, and III—from highest abrasion resistance to lowest abrasion resistance.

24.7 BOND PATTERNS IN MASONRY WALLS

Bricks can be assembled in a wall in several patterns, referred to as *bond patterns* or simply as *bonds*. The purpose of a bond is functional as well as aesthetic. Functionally, the bond is meant to stagger the units so that the load on one unit is shared by an increasing number of underlying units. A one-*wythe* masonry wall (a wall whose thickness equals the width, W, of one unit), built from whole (uncut) units, can have two types of bonds, Figure 24.18:



The staggering of masonry units and gravity load distribution. Also see Expand Your Knowledge in Section 25.1.

- Running bond
- Stack bond

A stack bond is commonly used at a sharply curved corner, Figure 24.19(a). It is also used for aesthetic reasons, Figure 24.19(b). The (horizontal) bending strength of a stack-bond wall is lower than that of a running-bond wall. Therefore, a stack-bond wall must be provided with horizontal reinforcement.

The bricks used in a stack-bond wall should have as much dimensional uniformity as possible so that the mortar joints have the least variation in width, Figure 24.20.

BRICK ORIENTATIONS ON WALL ELEVATION

In Figure 24.18, the bricks have only one orientation. The orientation refers to the exposed face of the brick. The exposed face of the brick in Figure 24.18 is called the *stretcher face* or simply the *stretcher*. Being a six-faced figure, a brick can have six different face orientations on a wall elevation, Figure 24.21:

- Stretcher
- Header
- Rowlock
- Soldier
- Shiner
- Sailor

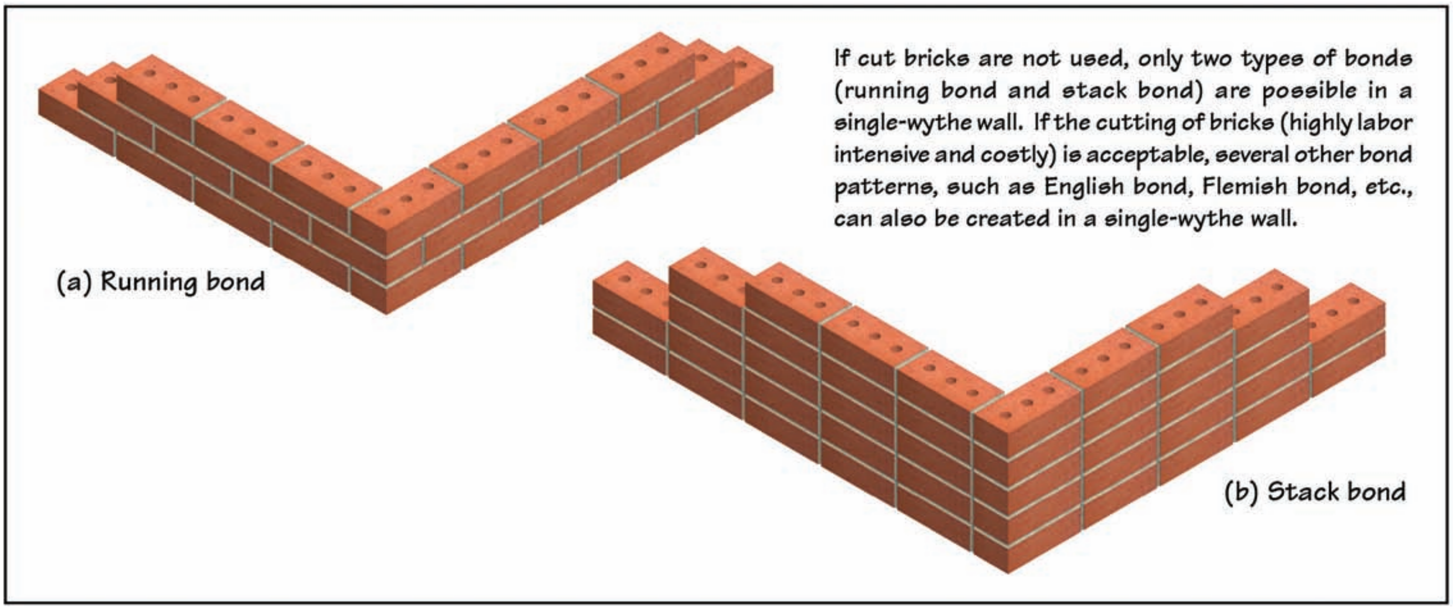
When a course of masonry consists of stretchers only (as in the running-bond and stack-bond walls of Figure 24.18), it is called a *stretcher course*. If it consists of headers only, it is called a *header course*, and so on. Single-wythe walls are generally made of all stretcher courses (Figure 24.18) and are often terminated at the top with one or more soldier courses to cover the core holes, Figure 24.22.

NOTE

The Terms: Masonry Wythe and Masonry Course

A masonry *wythe* is a vertical section of masonry that is one unit thick. The walls shown in Figure 24.18 are both one-wythe walls. Thus, if a wall is built of modular bricks and its thickness is 4 in. nominal, it is a one-wythe wall. If the wall is 8 in. (nominal) thick, it is a two-wythe wall. A 12-in.-thick wall is a three-wythe wall, and so on. The walls shown in Figure 24.23 are two-wythe walls.

A masonry *course* is a horizontal layer of masonry units. The English and Flemish bond walls of Figures 24.23(a) and (b) consist of four courses. The wall of Figure 24.23(c) consists of 14 courses.



If cut bricks are not used, only two types of bonds (running bond and stack bond) are possible in a single-wythe wall. If the cutting of bricks (highly labor intensive and costly) is acceptable, several other bond patterns, such as English bond, Flemish bond, etc., can also be created in a single-wythe wall.

FIGURE 24.18 Single-wythe walls in **(a)** running bond and **(b)** stack bond.

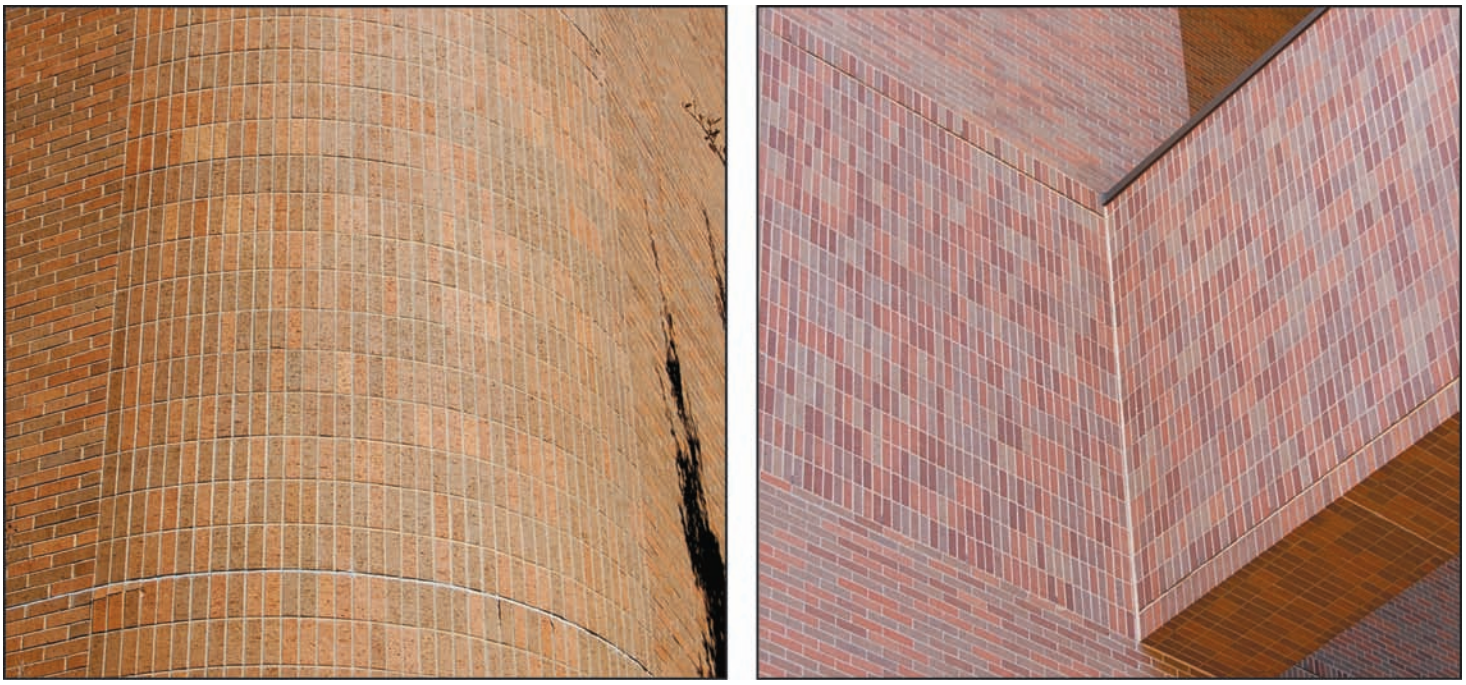


FIGURE 24.19 A stack-bonded brick wall used **(a)** to achieve a sharp curve and **(b)** for aesthetic reasons.

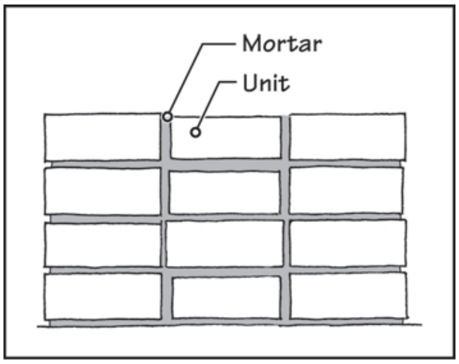

Mortar
Unit

FIGURE 24.20 A stack-bonded wall with large variations in masonry unit sizes is visually unacceptable.

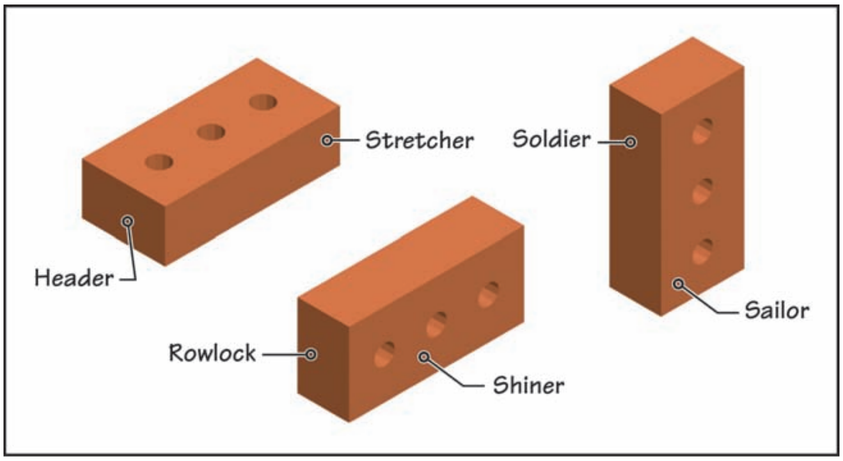

Stretcher
Soldier
Header
Sailor
Rowlock
Shiner

FIGURE 24.21 Terms used to distinguish among the six orientations of a brick unit in a wall elevation.

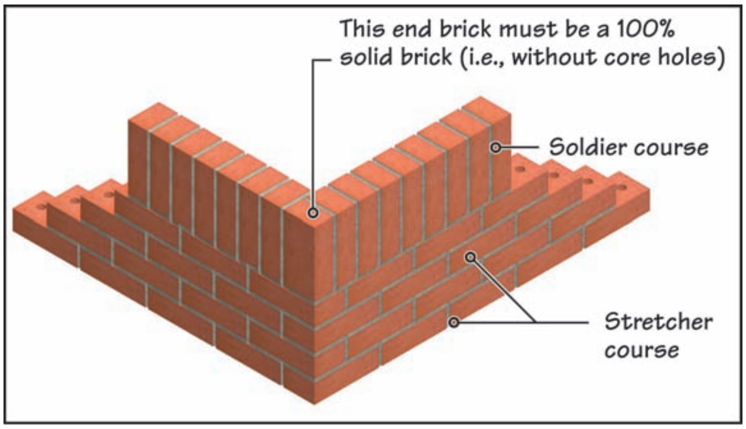

This end brick must be a 100% solid brick (i.e., without core holes)
Soldier course
Stretcher course

FIGURE 24.22 A single-wythe wall is often terminated with a soldier course at the top to cover the core holes in stretcher courses.

ENGLISH, FLEMISH, AND COMMON (AMERICAN) BONDS

As stated previously, contemporary brick masonry is used mainly as cladding. Therefore, most brick walls are one-wythe walls in running bond. However, fence walls are generally two-wythe walls or sometimes three-wythe walls. In two- or multiple-wythe walls, several bond patterns are possible.

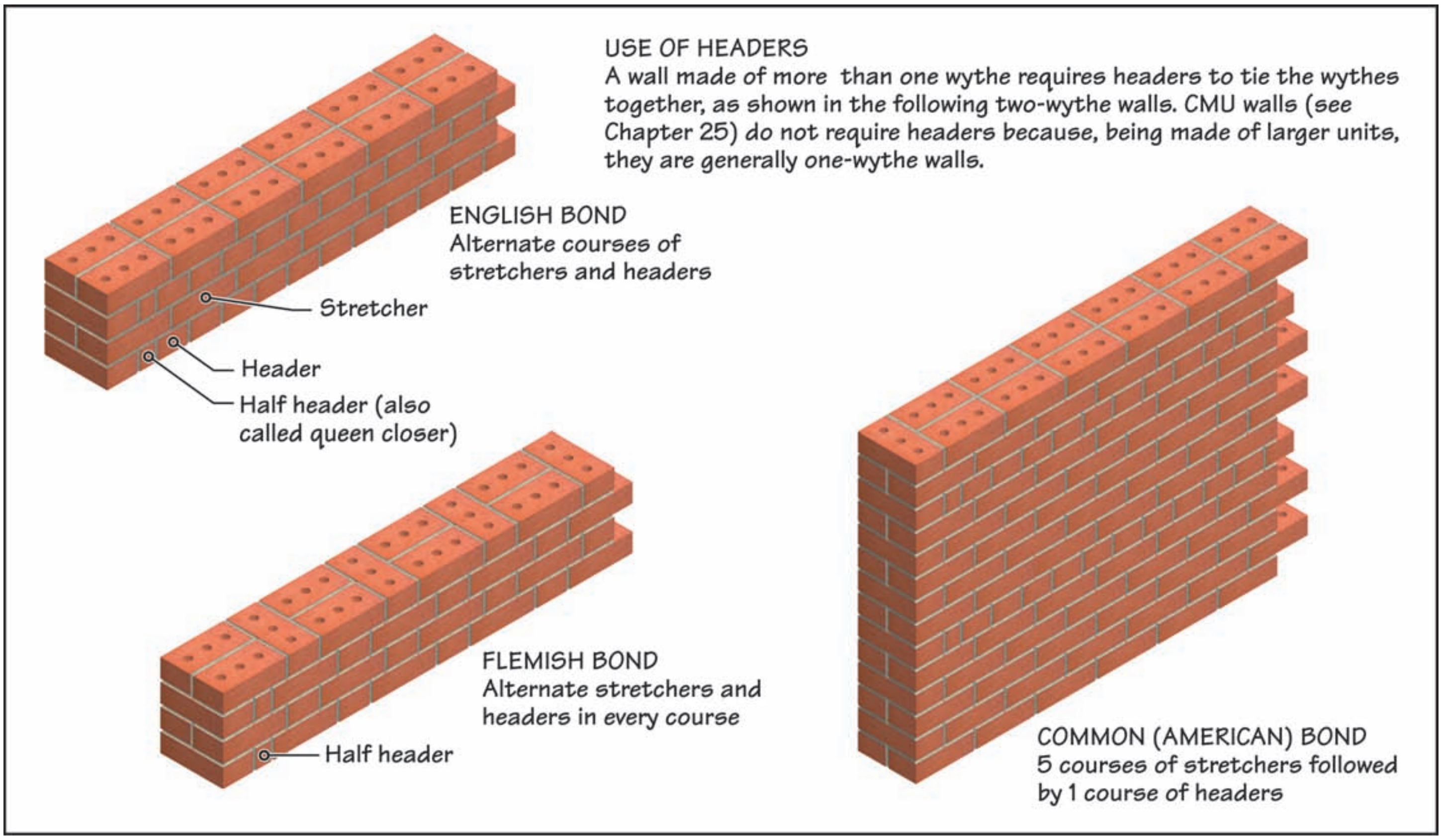

USE OF HEADERS
A wall made of more than one wythe requires headers to tie the wythes together, as shown in the following two-wythe walls. CMU walls (see Chapter 25) do not require headers because, being made of larger units, they are generally one-wythe walls.
ENGLISH BOND
Alternate courses of stretchers and headers
Stretcher
Header
Half header (also called queen closer)
FLEMISH BOND
Alternate stretchers and headers in every course
Half header
COMMON (AMERICAN) BOND
5 courses of stretchers followed by 1 course of headers

FIGURE 24.23 Two-wythe brick walls—in English, Flemish, and Common bonds.

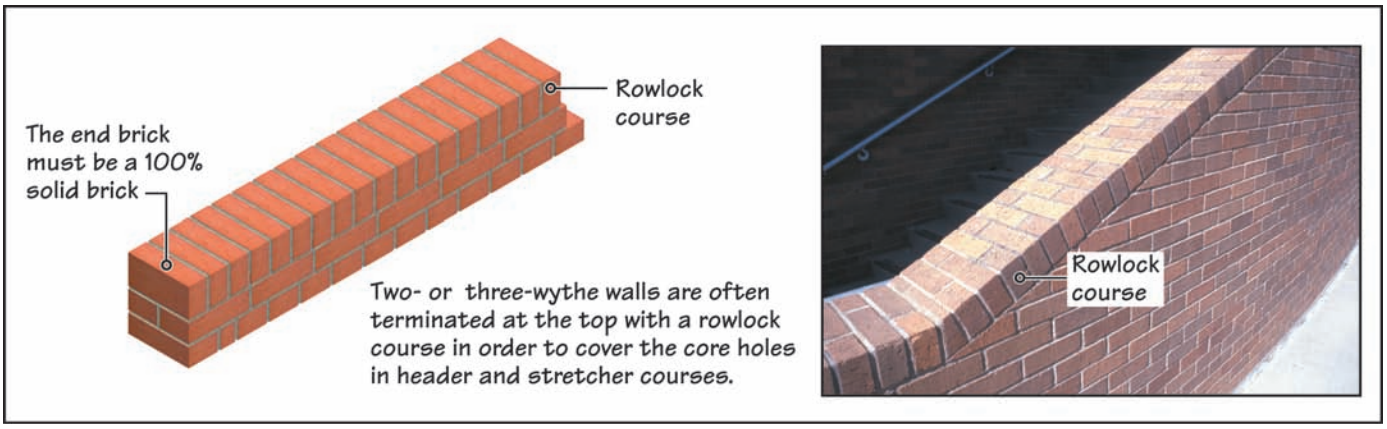

The end brick must be a 100% solid brick
Rowlock course
Two- or three-wythe walls are often terminated at the top with a rowlock course in order to cover the core holes in header and stretcher courses.
Rowlock course

FIGURE 24.24 Rowlock course as the terminal course in multiwythe brick walls.

Three commonly used bonds are the *English bond, Flemish bond*, and *American bond*, Figure 24.23. An English bond consists of alternate courses of headers and stretchers. In Flemish bond, there are alternate headers and stretchers in each course. In common (American) bond, there is a header course after every five courses of stretchers.

Just as a single-wythe wall is terminated with a soldier course to cover the core holes, a two-wythe wall is terminated with a rowlock course, Figure 24.24. Alternatively, a precast concrete or stone coping may be used as termination.

The bonds shown in Figure 24.23 use headers to tie the two wythes of masonry. If a header-tied masonry wall is used in a heated or cooled building where the interior and exterior faces of the wall have a large temperature difference, the headers can break. Therefore, in contemporary masonry, English, Flemish, or American bonds, are normally used in fence walls in which the opposite faces are not exposed to temperature differentials.

24.8 THE IMPORTANCE OF THE INITIAL RATE OF ABSORPTION (IRA) OF BRICKS

If bricks are too porous, they can suck too much water out of the mortar, leaving insufficient water for the hydration reaction (between Portland cement and water). This can weaken the mortar and, hence, the wall. Bricks that are highly absorptive must, therefore, be wetted with water prior to being laid in the wall. The wetting of bricks should be such that the interior of the brick is moist but the exterior surfaces of the brick are dry.

The preferred way of wetting absorptive bricks is to let water run on the pile of bricks so that the bricks become wet. Depending on the weather, this may be done the evening before (or a few hours before) the bricks are laid. This ensures that the interiors of the bricks are wet but the exteriors are dry. Bricks that are wet on the surface tend to float on the mortar bed and may also bleed water out of the mortar.

Bricks that are not highly absorptive do not need wetting and can be laid dry. Brick specifications use a measure referred to as the *initial rate of absorption* (IRA) to determine whether the bricks require wetting or not. If IRA >30 g/min/30 in.^{2}, the bricks should be wetted prior to laying; otherwise, not. (Note that in colder regions, wetting the bricks may not be appropriate.)

24.9 THE CRAFT AND ART OF BRICK MASONRY CONSTRUCTION

The construction of a brick wall can appear deceptively simple to a lay observer, particularly in the hands of an expert mason. Compared to wood framing or concrete placing, however, the construction of brick walls requires much greater skill and craft. Additionally, it is slow and labor intensive. To speed construction, several masons work simultaneously on building a wall. This requires coordination and quality control to ensure uniform workmanship.

The first step in constructing a brick wall is to lay the corners. The string line is then stretched between the corners and the bricks are laid to the string line, maintaining a level and plumb wall. In addition to the string line, the primary tools used by a mason are a trowel and a level. Some masons use a story pole to give uniformity in course heights.

The mortar joints are tooled after the mortar has become sufficiently hard but is still pliable (referred to as *thumbprint hard*). Figure 24.25 shows a typical sequence of steps involved in constructing a brick wall.

NOTE

Retempering Mortar

Retempering mortar (adding of water to unused mortar that has somewhat dried) is acceptable provided that the mortar has not stiffened excessively. In general, mortar should be prepared immediately prior to its use. If needed, the plastic life of unused mortar can be extended somewhat by covering it with a plastic sheet.

Retempering reduces the strength of mortar, but if it is done within $2\frac{1}{2}$ h of initial preparation, the results are acceptable. Therefore, mortar prepared more than $2\frac{1}{2}$ h (depending on the weather) prior to its use should be discarded. Retempering colored mortar may result in undesirable color variation.

REPOINTING OF MORTAR JOINTS

Mortar may deteriorate due to freeze-thaw action and/or erode from water. This leads to receding joint depth, resulting in a leaky wall. The recessed joints need to be refilled with mortar—a process referred to as *repointing*.

Repointing of mortar joints used to be far more common when lime mortar was used. It is relatively rare in contemporary masonry because of the use of some Portland cement in mortar. However, there are situations, particularly with Type O mortar, in which the joints in some masonry walls may need repointing. Repointing involves raking the existing joints and filling them with mortar.

Raking involves grinding into the joint to obtain adequate depth (typically, twice the mortar joint thickness) and filling the joint with the new mortar, Figure 24.26. Before filling of the joint, the joint is wetted to improve the bond between the existing and new mortar.

EXPAND YOUR KNOWLEDGE

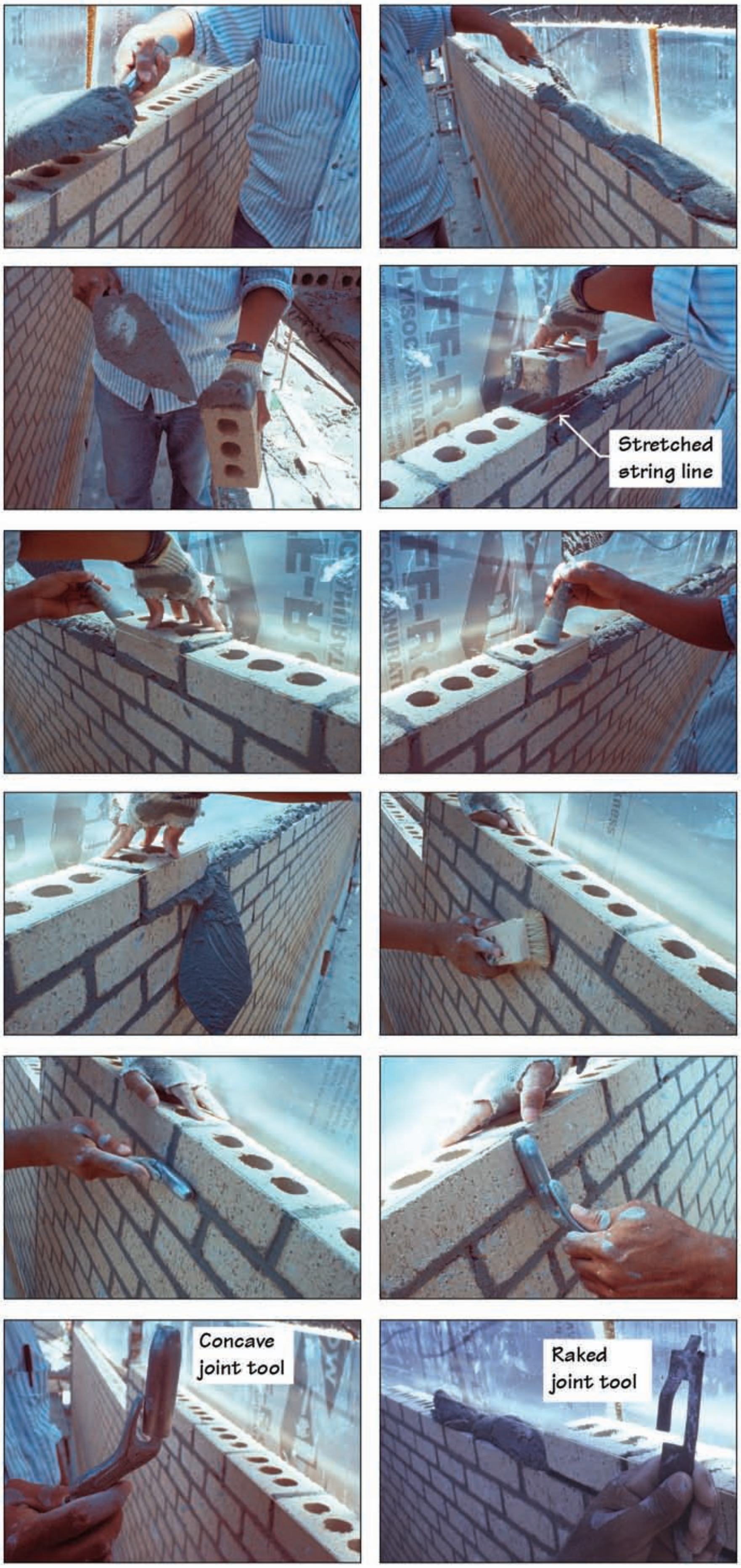
Initial Rate of Absorption (IRA) and Its Measurement

The IRA is obtained by immersing a dry brick in water to a depth of $\frac{1}{8}$ in. The immersion is done for only 1 min, after which the brick is removed. The brick is weighed before and after immersion. If the weight of the dry brick is W_d and that of the wet brick is W_w, then IRA is given by:

$$\text{IRA} = \frac{W_w - W_d}{A_n}(30 \text{ in.}^2)$$

where A_n = the immersed area of the brick

If IRA >30 g/min/30 in.^{2} of the brick's immersed surface area, the bricks should be wetted; otherwise, not. A surface area of 30 in.^{2} has been chosen because it gives a convenient figure of 1 g of water absorption per square inch of a brick's surface.



The mason spreads the mortar over a previously laid brick course. In the case of a brick veneer wall (shown here), the mason ensures that little or no mortar falls in the air space behind the veneer.

The mason picks up a brick to be laid and mortars ("butters"—a term used by the masons for mortaring) the head joint of the brick before laying it in the wall. Some masons will fully butter the head joint of the brick to be laid. Other masons will fully butter the head joint of the already-laid brick, and butter the brick to be laid with just two stripes. In any case, all joints must be fully mortared.

Using the trowel handle, the mason presses the freshly laid brick against the adjacent bricks to give a better bond and a more watertight mortar joint.

Using the trowel, the mason removes the extra mortar that has been squeezed out of the joint. Because the mortar has good water retentivity, very little mortar sticks to the brick face. However, the brick face is cleaned with a brush after the mortar has somewhat dried.

After the mortar has stiffened (referred to as "thumb-print hard" in the industry), the mason tools the joints. In this photograph, the tooling is being done to obtain concave joints.

The left-side image shows a concave joint tool and the right-side image shows a raked joint tool.

FIGURE 24.25 Steps involved in constructing a single-wythe brick wall.

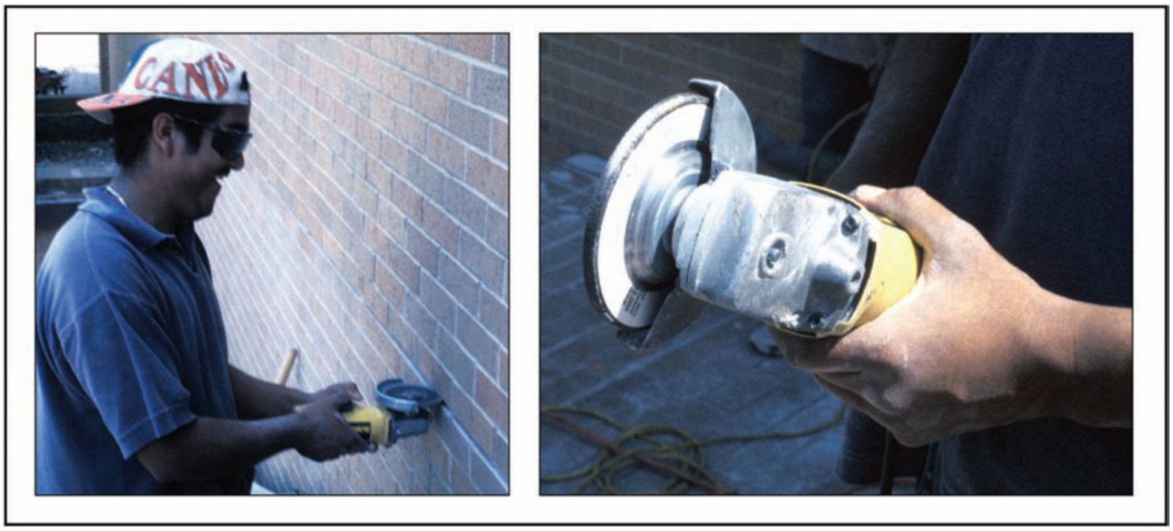


FIGURE 24.26 Grinding of mortar joints in preparation for repointing a brick wall.

24.10 EFFLORESCENCE IN BRICK WALLS

Efflorescence is the deposit of a white substance on a masonry wall. This substance consists of water-soluble salts, present in masonry units, in the mortar, or both, which migrate to the outside of the units as the water evaporates, Figure 24.27. Efflorescence does not generally create any structural or sanitation problem, but it is unsightly.

Although efflorescence may occur in both concrete and clay masonry, it is more common and more obvious in brick masonry walls because of the dark color of bricks. The likelihood of efflorescence can be reduced by selecting masonry units that have been tested for the absence of soluble salts (per ASTM C67).

Efflorescence may also originate from mortar due to soluble salts in water or sand. Minor efflorescence can be removed by washing the wall, allowing it to dry, and then brushing off the dry salt. Repeating this cycle a few times should leach out all the salts. Efflorescence that appears several years after the wall was built could be due to unclean water penetrating the wall, such as from a lawn sprinkler system, or leakage from a roof.

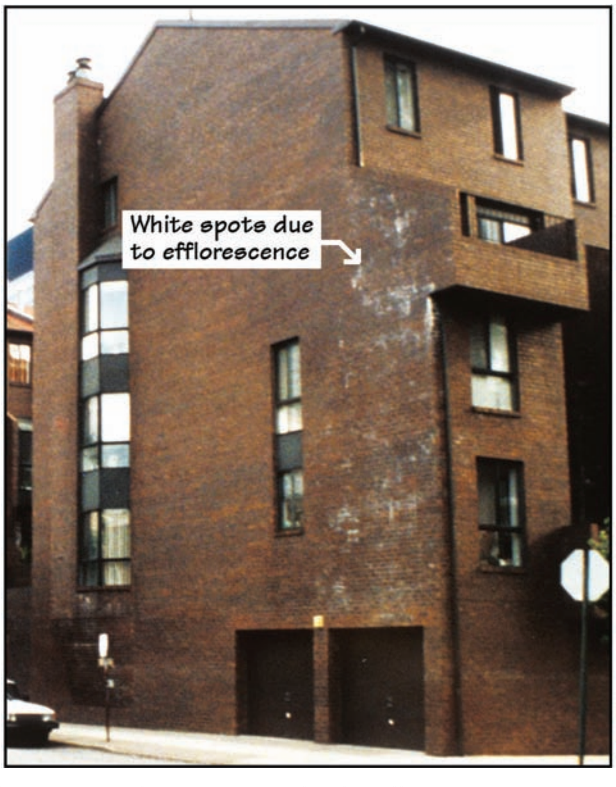


FIGURE 24.27 Efflorescence (white spots) on a brick wall.

24.11 EXPANSION CONTROL IN BRICK WALLS

As described in Chapter 9, brick walls expand irreversibly due to the absorption of moisture. They also expand or contract due to temperature changes and foundation settlements. Therefore, brick masonry is divided into segments, with continuous vertical joints between the segments. Because expansion of brick walls is more dominant than contraction, the vertical joints are detailed as expansion joints.

Most brick masonry is used as veneer in the exterior cladding of buildings, covered in chapter 28. Expansion control of brick veneer is covered in that chapter.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

27. Per ASTM standards, facing bricks are classified as Types FBS, FBX, and FBA. Which of these types has the most stringent requirements for dimensional tolerance, chippage, and warpage?
a. FBS **b.** FBX
c. FBA

28. The freeze-thaw resistance of bricks has been found to be a function of the
a. compressive strength of bricks.
b. boiling-water absorption of bricks.
c. saturation coefficient (SC) of bricks.
d. all of the above.
e. (a) and (b).

29. The weathering index (WI) of a location is a function of the
a. average annual freezing-cycle days.
b. average annual winter rainfall of the location.
c. average annual air temperature of the location.
d. all of the above.
e. (a) and (b).

30. In a running-bond wall
a. each course consists of headers.
b. each course consists of stretchers.
c. each course consists of alternate headers and stretchers.
d. the courses alternate between headers and stretchers.
e. none of the above.

31. In an English-bond wall,
a. each course consists of headers.
b. each course consists of stretchers.
c. each course consists of alternate headers and stretchers.
d. the courses alternate between headers and stretchers.
e. none of the above.

32. In a Flemish-bond wall,
a. each course consists of headers.
b. each course consists of stretchers.
c. each course consists of alternate headers and stretchers.
d. the courses alternate between headers and stretchers.
e. none of the above.

33. IRA is a measure of the tensile strength of a brick.
a. True **b.** False

34. Bricks that are highly absorptive may need to be wetted before being laid in the wall.
a. True **b.** False

35. Retempering of mortar means
a. adding Portland cement to mortar.
b. adding lime to mortar.
c. adding sand to mortar.
d. adding water to mortar.

36. Retempering of mortar, if needed, should be generally done within
a. $5\frac{1}{2}$ h of the initial preparation of mortar.
b. 4 h of the initial preparation of mortar.
c. $2\frac{1}{2}$ h of the initial preparation of mortar.
d. 1 h of the initial preparation of mortar.
e. none of the above.

37. Efflorescence in masonry refers to
a. excessive chippage of masonry units.
b. excessive warpage of masonry units.
c. white spots in masonry walls.
d. yellow spots in masonry walls.
e. none of the above.

REVIEW QUESTIONS

1. Describe the importance of lime in mortar.
2. Describe the importance of Portland cement in mortar.
3. Give the ASTM classification of mortar types and their respective applications.
4. Explain why the masonry industry recommends the use of the weakest mortar that will give the required performance.
5. Using sketches and notes, describe various commonly used mortar joint profiles. Which profile gives the most watertight wall and why?
6. Explain the difference among the actual, nominal, and specified dimensions of masonry units.
7. Bricks may carry a grade of SW, MW, or NW. Which factors determine the grade?
8. Explain what the weathering index (WI) means, and how it relates to building construction.
9. Explain what efflorescence is and how it can be mitigated.

CHAPTER 25

Masonry Materials–II (Concrete Masonry Units, Natural Stone, and Glass Masonry Units)

CHAPTER OUTLINE

25.1 CONCRETE MASONRY UNITS—SIZES AND SHAPES

25.2 CONCRETE MASONRY UNITS—MANUFACTURING AND SPECIFICATIONS

25.3 CONSTRUCTION OF A CMU WALL

25.4 SHRINKAGE CONTROL IN CMU WALLS

25.5 GROUT

25.6 NATURAL STONE

25.7 FROM BLOCKS TO FINISHED STONE

25.8 STONE SELECTION

25.9 FIRE RESISTANCE OF MASONRY WALLS

This chapter is a continuation of the previous chapter and deals with masonry materials not covered there—concrete masonry units, natural stone, and glass masonry units. Because joint reinforcement and grout are an integral part of most concrete masonry walls, these are also discussed in this chapter.

Steel reinforcement, used in reinforced masonry, is the same as that used in reinforced concrete construction and was covered in Chapter 21. Masonry construction systems are discussed in Chapters 26 and 28.

25.1 CONCRETE MASONRY UNITS—SIZES AND SHAPES

Concrete masonry units (CMUs) are made of concrete and are, therefore, also called concrete blocks. They are more complex than (clay) bricks and are available in a much larger number of surface finishes and colors.

A CMU is also a much larger unit than a brick. An 8-in.-wide CMU, a more commonly used CMU size, occupies the same amount of space as 12 modular bricks, Figure 25.1(a). Thus, the laying of a CMU is equivalent of laying 12 bricks, which reduces the labor cost in constructing a wall. Because of its size, a CMU is much heavier than a brick. Therefore, the laying of a CMU is a two-hand operation versus the one-hand operation used in laying a brick, Figures 25.1(b) and 25.1(c). In fact, the term “brick” implies a unit that is laid using one hand regardless of the material of which it is made. Thus, the difference between “concrete brick” and “concrete block” is only one of the relative sizes of units.

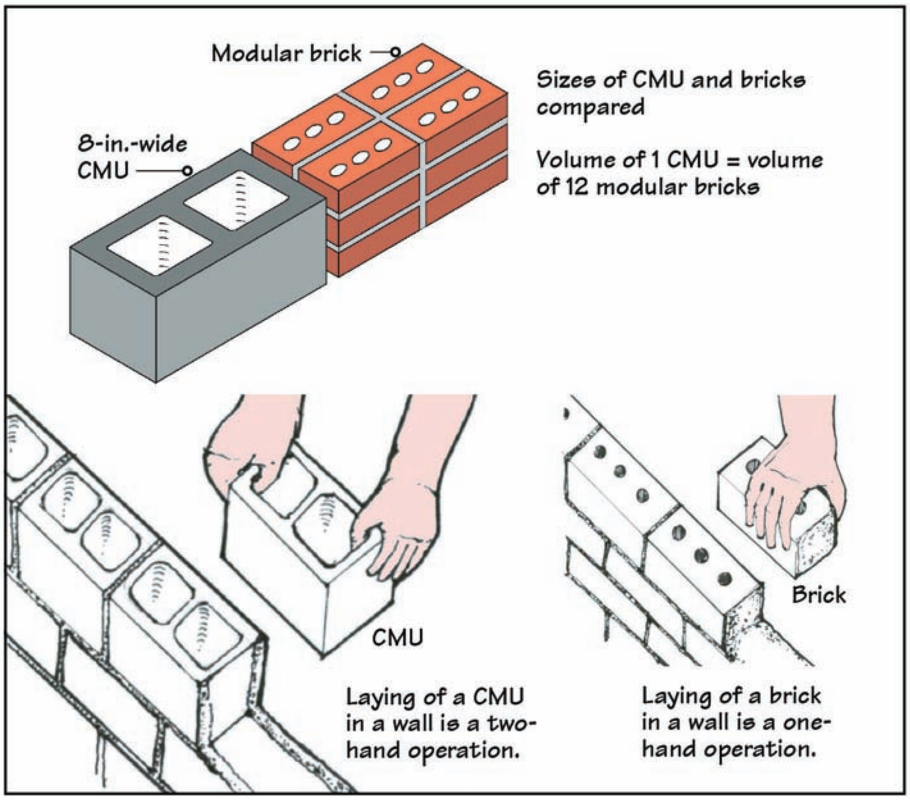

Modular brick
Sizes of CMU and bricks compared
Volume of 1 CMU = volume of 12 modular bricks
8-in.-wide CMU
CMU
Brick
Laying of a CMU in a wall is a two-hand operation.
Laying of a brick in a wall is a one-hand operation.

FIGURE 25.1 A CMU, also called *concrete block*, is much larger than a brick and also much heavier. Therefore, the laying of a CMU in a wall is a two-hand operation. A brick, on the other hand, is laid using one hand.

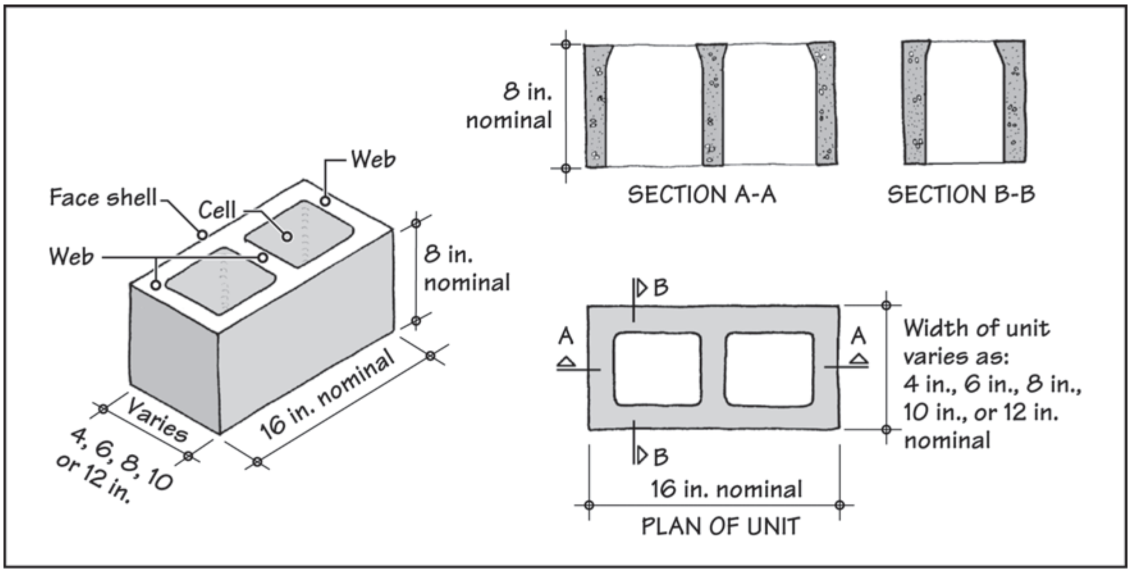
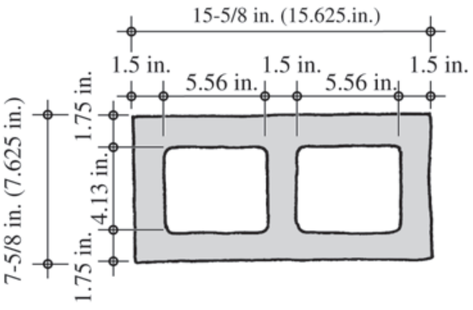

Web
Face shell
Cell
Web
8 in. nominal
Varies 4, 6, 8, 10 or 12 in.
16 in. nominal
8 in. nominal
SECTION A-A
SECTION B-B
B
A
A
B
Width of unit varies as: 4 in., 6 in., 8 in., 10 in., or 12 in. nominal
16 in. nominal
PLAN OF UNIT

FIGURE 25.2 Sizes of CMUs.


15-5/8 in. (15.625.in.)
1.5 in.
5.56 in.
1.5 in.
5.56 in.
1.5 in.
1.75 in.
4.13 in.
1.75 in.
7-5/8 in. (7.625 in.)

Assuming that the average thickness of face shells and webs is 1.75 in. and 1.5 in., respectively, the cells in a typical 8-in. unit are 4.13 in. × 5.56 in. = 23 in.^{2}

As shown later in this chapter, the voids in a CMU wall are continuous through its height. This arrangement allows the voids to be filled with grout (which is like concrete) and reinforced vertically—a requirement for load-bearing walls and walls required to resist lateral loads. Unlike clay bricks, which are generally used in face veneers, CMUs are used in both structural and face veneer applications.

SIZES OF CMUs

CMUs are available in several different sizes. The shape of a typical unit is shown in Figure 25.2. The length and height of all units are generally the same: length = 16 in. nominal ($15\frac{5}{8}$ in. specified) and height = 8 in. nominal ($7\frac{5}{8}$ in. specified). The width varies from 4 in. to 12 in. nominal in steps of 2 in., that is, width = 4, 6, 8, 10, 12, or 14 in. Because the length and height of a CMU are generally fixed, a CMU's size is generally specified by its width. An 8-in.-wide unit is most commonly used.

The face shells and the webs of a unit are generally flared at the top of the unit as laid in the wall. Thus, a unit has a top and a bottom. The taper helps the mason in lifting and placing the unit in a wall. ASTM specifications provide a minimum thickness of face shells and webs for CMUs of different sizes. For example, an 8-in. CMU must have a minimum face shell thickness of $1\frac{1}{4}$ in. at the thinnest point and a 1-in. minimum thickness for the webs.

The voids in a CMU are called *cells*. Most manufacturers make a two-cell CMU. The longitudinal walls of a CMU are called *face shells*, and the transverse walls are called *webs*. Thus, a two-cell unit has three webs. In an 8-in. unit, the cells are approximately 23 in.^{2}—a space that is large enough for reinforcing and grout (see Section 25.5 for a discussion of grout).

SCORED, BULLNOSE, AND SASH UNITS, AND UNITS WITH PROJECTING FACE SHELLS

Various shapes of CMUs are available to serve different functions in a wall. A typical manufacturer may make 20 or more different shapes and several different finishes. When all sizes, shapes, surface finishes, and colors are considered, a CMU manufacturer may have hundreds of different products.

Although the unit shape of Figure 25.2 constitutes the bulk of a CMU wall, a half-unit is required at the end of a wall, Figure 25.3, and is generally provided as a standard unit by the manufacturers. Where an odd-dimension unit is needed, a full-size unit may be sawed at the site. The sawing of units is time consuming and labor intensive and raises the cost of construction.

Figure 25.4 shows a bullnose unit and a scored unit. Bullnose units are used where a sharp wall corner is to be avoided. When scored units are used, the wall has the appearance of a stack-bond wall but the strength of a running-bond wall, Figure 25.5 (see also Figure 25.23).

The units shown in Figure 25.6 (top) have projecting face shells at one or both ends. They are generally used interchangeably with the flush-end units of Figure 25.2. However, as described later, a CMU is generally mortared on face shells only. The projecting face shells make it more convenient to mortar the head joints. Units with projecting face shells are also used in control joints (see Figures 25.25 and 9.18). Control joints can also be made with sash units, Figure 25.6 (bottom).

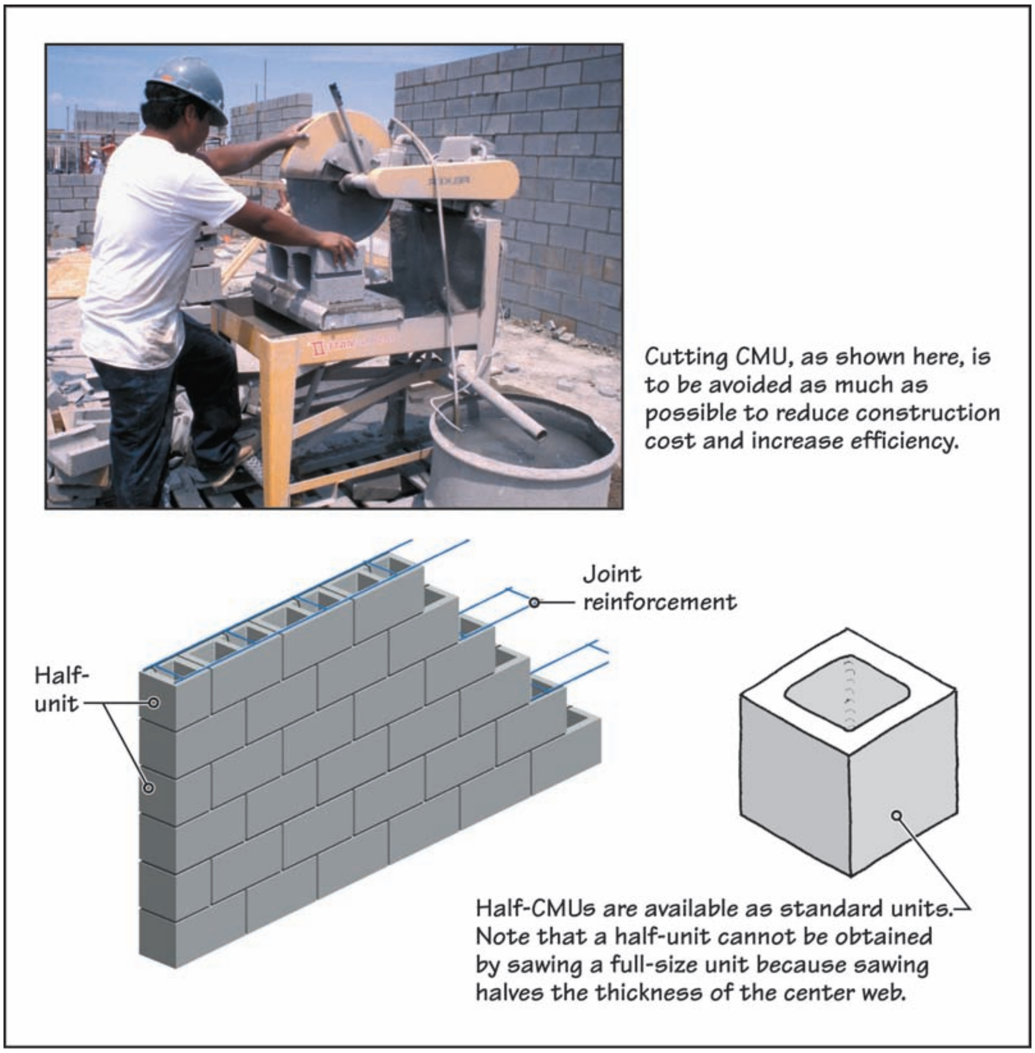

Cutting CMU, as shown here, is to be avoided as much as possible to reduce construction cost and increase efficiency.
Joint reinforcement
Half-unit
Half-CMUs are available as standard units. Note that a half-unit cannot be obtained by sawing a full-size unit because sawing halves the thickness of the center web.

FIGURE 25.3 Half-units and their use in a wall.

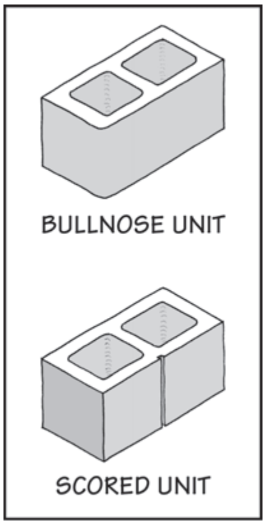

BULLNOSE UNIT
SCORED UNIT

FIGURE 25.4 Bullnose and scored units.

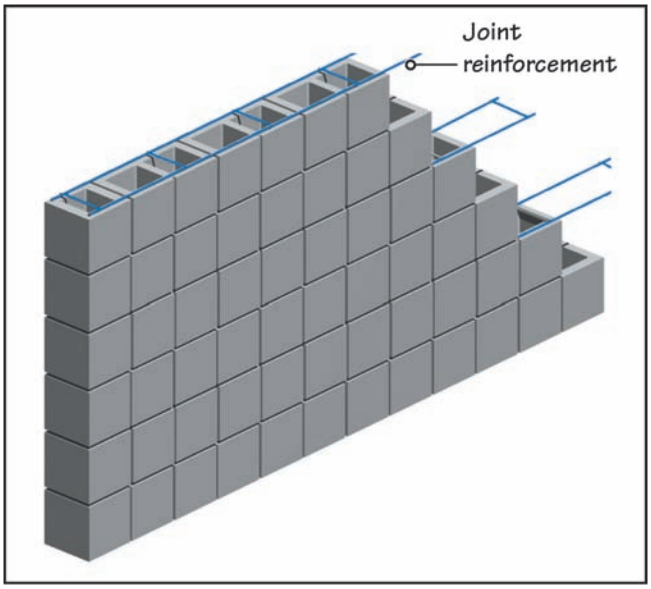

Joint reinforcement

FIGURE 25.5 The use of scored units in a wall.

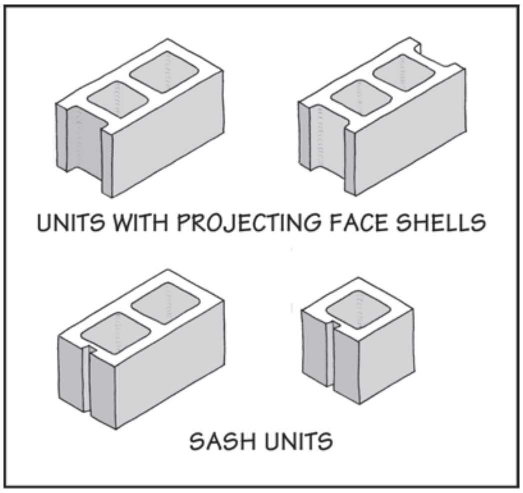

UNITS WITH PROJECTING FACE SHELLS
SASH UNITS

FIGURE 25.6 CMUs with projecting face shells and sash units. CMUs with projecting face shells on one or both ends can be substituted for the plain-end units (Figure 25.2) and can also be used in control joints (see Figure 25.25).

LINTEL UNIT

A lintel unit is U-shaped, Figure 25.7. When grouted and reinforced horizontally, several lintel units in the same course function like a concrete beam that can be used to span an opening. For a large opening requiring a deeper lintel, some manufacturers make a 16-in.-high (two-course-high) unit.

A 16-in.-deep lintel can also be constructed by using an 8-in.-high lintel unit and fully grouting the lintel course and the course immediately above it. Similarly, a 24-in.-deep

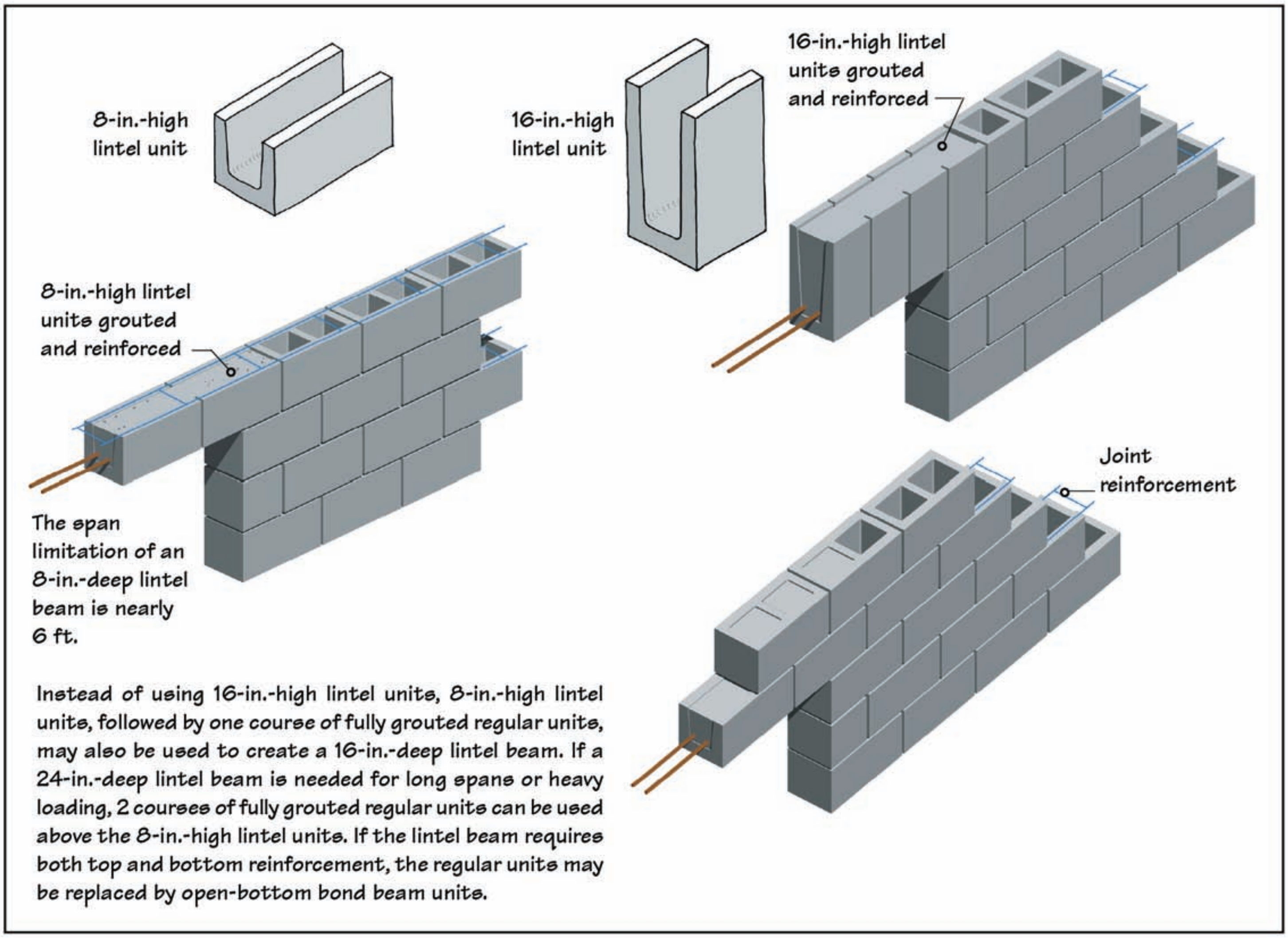

8-in.-high lintel unit
16-in.-high lintel unit
16-in.-high lintel units grouted and reinforced
8-in.-high lintel units grouted and reinforced
The span limitation of an 8-in.-deep lintel beam is nearly 6 ft.
Joint reinforcement
Instead of using 16-in.-high lintel units, 8-in.-high lintel units, followed by one course of fully grouted regular units, may also be used to create a 16-in.-deep lintel beam. If a 24-in.-deep lintel beam is needed for long spans or heavy loading, 2 courses of fully grouted regular units can be used above the 8-in.-high lintel units. If the lintel beam requires both top and bottom reinforcement, the regular units may be replaced by open-bottom bond beam units.

FIGURE 25.7 Concrete masonry lintels.

lintel can be obtained by grouting two courses of masonry above the standard 8-in.-high lintel.

Lintels in a CMU wall may also be made of steel, precast concrete, or site-cast concrete. Concrete masonry lintels have the advantage of maintaining the bond pattern, color, and surface texture of the wall.

EXPAND YOUR KNOWLEDGE

Arching Action in Masonry Walls

Masonry walls are generally built in running bond, English bond, Flemish bond, and so on. In all of these bond patterns, the head joints are staggered so that a concentrated gravity load, as it travels down toward the foundation, is distributed over an increasingly larger number of masonry units, Figure 1. In other words, a vertical load placed on a wall is directed downward at a 45° angle on either side of the load, Figure 2.

The 45° flaring of the load in masonry walls is referred to as the *arching action* because the phenomenon is similar to the behavior of an arch, which transfers the gravity loads placed on it to side abutments. Arching action occurs in all masonry walls in which the head joints in one course are (sufficiently) staggered from those in the upper and lower courses. Arching action is altogether absent in a dry-stacked, stack-bond wall. In a mortared stack-bond wall, some arching action occurs due to vertical shear transfer from one unit to the other through mortar joints, but it is ignored.

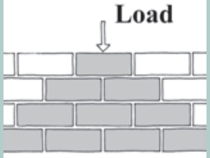


FIGURE 1

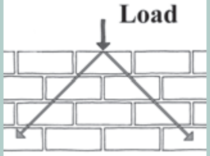


FIGURE 2

It is because of the arching action that sizable holes can be created in an existing masonry wall without causing the wall to collapse. The practical consequence of arching action is that a lintel beam (or simply a lintel) spanning an opening may not receive all of the load placed directly above it, Figure 3. If the height of masonry above the lintel is more than half the width of the opening (to enable a 45° triangle to be formed within the wall), the load carried by the lintel is only the load of the masonry within the 45° triangle, Figure 4.

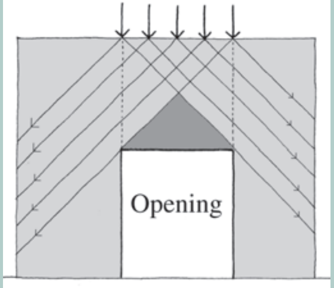


FIGURE 3 A load placed on the top of a masonry wall is directed downward, flaring at 45° from the vertical. The lintel over the opening, therefore, receives the load from the triangular (highlighted) area only.

In practice, a 12-in. depth of masonry above the apex of a 45° triangle is needed to assume a triangular load on the lintel. In other words, if the height of masonry above the lintel is half the lintel span plus 12 in., arching action is assumed and the lintel is designed for triangular loading plus the self-load of the lintel.

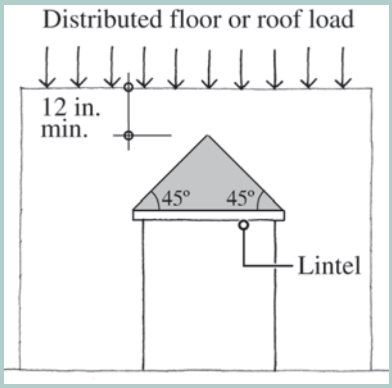


FIGURE 4 The lintel is designed to carry this triangular load of masonry plus the self-load of the lintel. The distributed superimposed (floor or roof) load on the top of the wall is not carried by the lintel. However, a concentrated load on the top of the wall, lying directly above the opening, must be considered a distributed load on the lintel.

An additional requirement for arching action is that abutments on either side of the opening are sufficiently thick to absorb the lateral thrust caused by the arching action.

If the wall in Figure 4 carries a distributed superimposed load (due to an overlying floor or roof), it is not carried by the lintel but by the wall on either side of the opening. Because this condition occurs commonly, the lintels over openings in masonry walls need only a small amount of steel reinforcement.

However, a concentrated load directly above the opening should be considered a concentrated load on the lintel.

In the absence of arching action, the lintel must be designed for the rectangular load of the wall plus any distributed and concentrated superimposed load above the lintel opening, Figure 5.

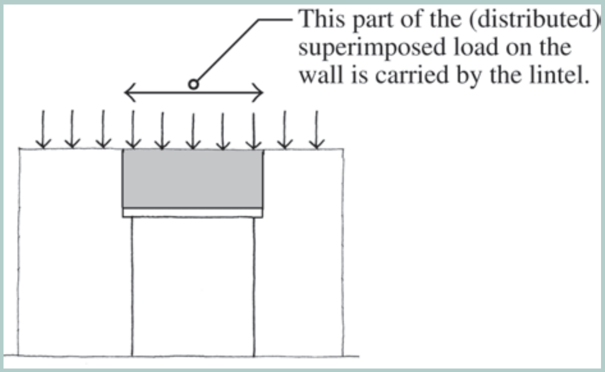

This part of the (distributed) superimposed load on the wall is carried by the lintel.

FIGURE 5 In the absence of arching action, the lintel must be designed to carry this rectangular load of masonry plus the self-load of the lintel and any (distributed and concentrated) superimposed wall load directly above the opening.

A-UNIT, H-UNIT, AND BOND BEAM UNIT

An A-unit is used in a reinforced concrete masonry wall, Figure 25.8. The use of an A-unit eliminates the need to place (string) the unit over the reinforcement or electrical conduit. An H-unit is used where every cell is reinforced. Because the cells in a concrete masonry wall are 8 in. on center, reinforcing each cell implies that the reinforcement in the wall is 8 in. on centers. A concrete masonry wall with reinforcement at 8 in. on centers is a fully grouted wall (no ungrouted cells). Note that a reinforced concrete masonry wall can have reinforcement only at 8 in., 16 in., 24 in., 32 in., and so on, on centers.

Some other commonly used CMUs are bond beam units and pilaster units, Figure 25.9. The use of bond beam units is illustrated later in this chapter (Section 25.4).

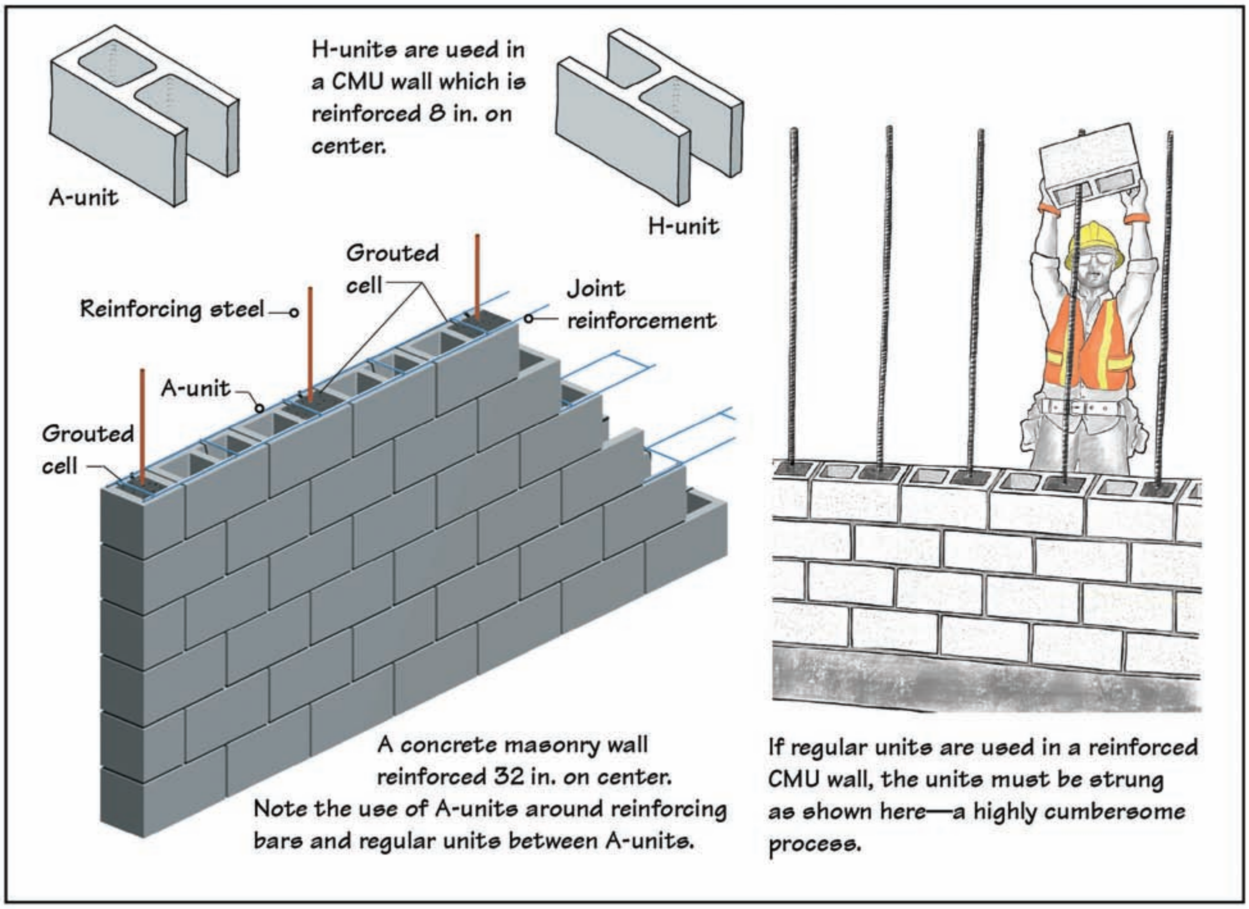

H-units are used in a CMU wall which is reinforced 8 in. on center.
A-unit
H-unit
Grouted cell
Reinforcing steel
Joint reinforcement
A-unit
Grouted cell
A concrete masonry wall reinforced 32 in. on center.
Note the use of A-units around reinforcing bars and regular units between A-units.
If regular units are used in a reinforced CMU wall, the units must be strung as shown here—a highly cumbersome process.

FIGURE 25.8 The use of A-units and H-units in a reinforced CMU wall.

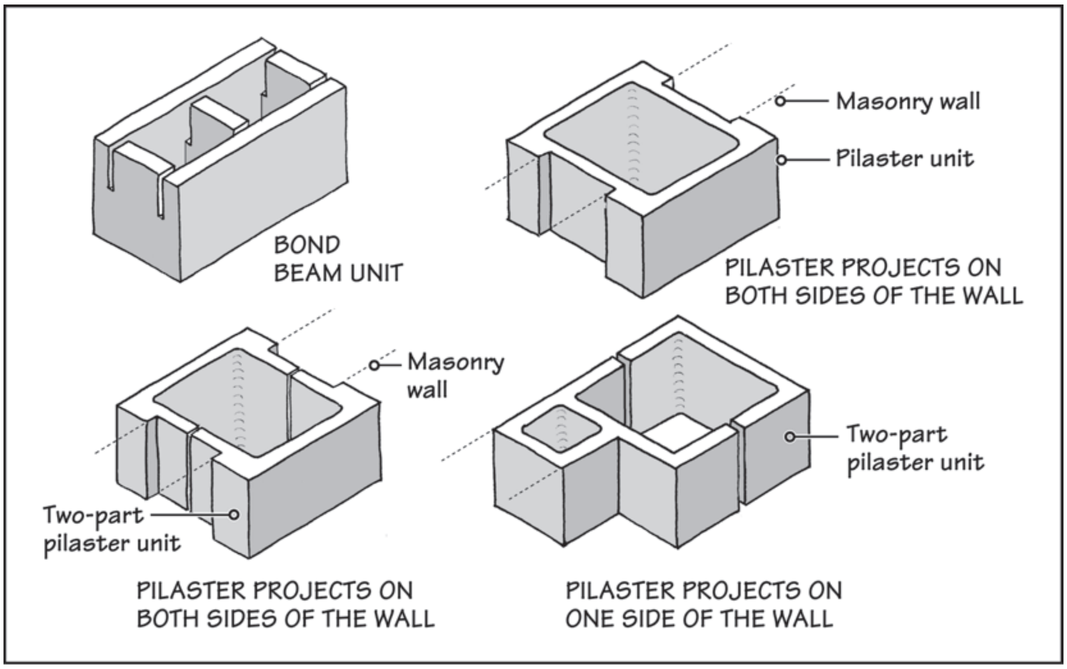

BOND BEAM UNIT
Masonry wall
Pilaster unit
PILASTER PROJECTS ON BOTH SIDES OF THE WALL
Masonry wall
Two-part pilaster unit
Two-part pilaster unit
PILASTER PROJECTS ON BOTH SIDES OF THE WALL
PILASTER PROJECTS ON ONE SIDE OF THE WALL

FIGURE 25.9 Bond beam unit and pilaster units.

ACOUSTICAL UNITS

An acoustical unit is commonly used where a concrete masonry wall with sound-absorptive properties is needed. It has fiberglass embedded behind open slits.

SURFACE TEXTURES—SPLIT-FACE UNIT AND RIBBED UNIT

CMUs can be provided with surface textures other than the (standard) smooth texture. A fairly rough texture is obtained in a split-face unit, Figure 25.10. A split-face unit mimics a rough, stonelike texture and is produced by fracturing a fully hardened double CMU with a guillotine, which produces two split-face units. Split-face units are available with rough texture on one face or on two adjacent faces (corner unit). Half-units are also available.

Another highly textured unit is the ribbed unit, which has several vertical ribs. A ribbed unit is also available as a split-face unit so that the ribs are not smooth, see Figure 25.10.

SURFACE FINISHES—BURNISHED UNIT AND GLAZED UNIT

The exposed surface of a CMU can be ground smooth to reveal the aggregate. Variations in aggregate color, size, and type and the use of integral pigments can produce a surface that resembles a smooth-surfaced granite. Ground-face CMUs are called *burnished units* and are often used in interiors where no additional finish is required. They can also be used in an exterior wall, often as accent bands in a wall made with split-face units, Figure 25.11.

A glazed unit has a facing of a glazing material bonded to one or more faces of the unit. The facing, approximately $\frac{1}{10}$ in. thick, is applied after the block has been made. The facing extends a little beyond the CMU face on all sides, Figure 25.12.

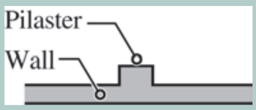
A glazed CMU surface is impervious to moisture and dust collection and is easy to clean, so it is sanitary. Glazed CMUs, which are available in various colors, are often used in hospital interiors, public kitchens, and so on—wherever surface cleanliness is important. The suitability of glazed CMUs on exteriors must be verified with the manufacturer to ensure color fastness and resistance to delamination by freeze-thaw action.

NOTE

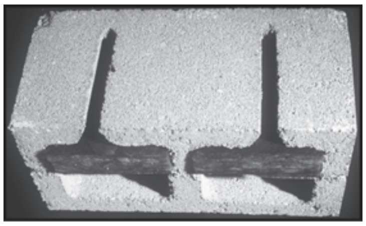
Pilasters, Columns, and Piers

Pilasters, columns, and piers are similar elements. However, a *column* refers to an independent, isolated, vertical load-bearing masonry or nonmasonry member. The term *pier* is generally used for a masonry column that is short in height, generally used as foundation for wood frame buildings with an underlying crawl space (see Chapter 12, e.g., Figure 12.24).

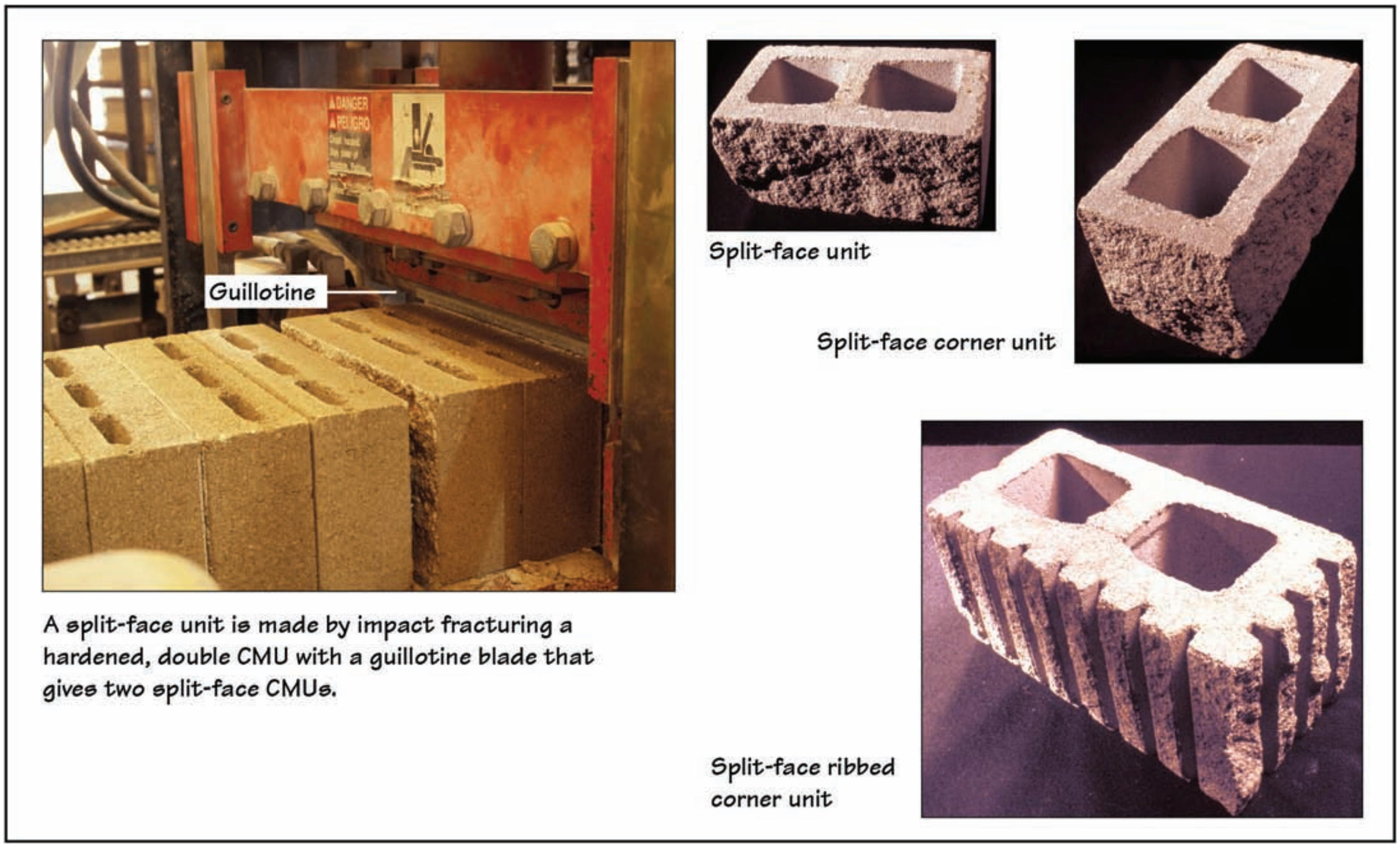
A *pilaster* is a column formed by thickening a small area of a masonry wall, which may project on one or both sides of the wall. Like a reinforced concrete column, a reinforced masonry column requires ties. A pilaster does not require ties unless it is provided with compression reinforcement.



Acoustical unit



Acoustical unit



A split-face unit is made by impact fracturing a hardened, double CMU with a guillotine blade that gives two split-face CMUs.

FIGURE 25.10 Various types of split-face units, made by impact fracturing a double CMU through the middle resulting into two units.

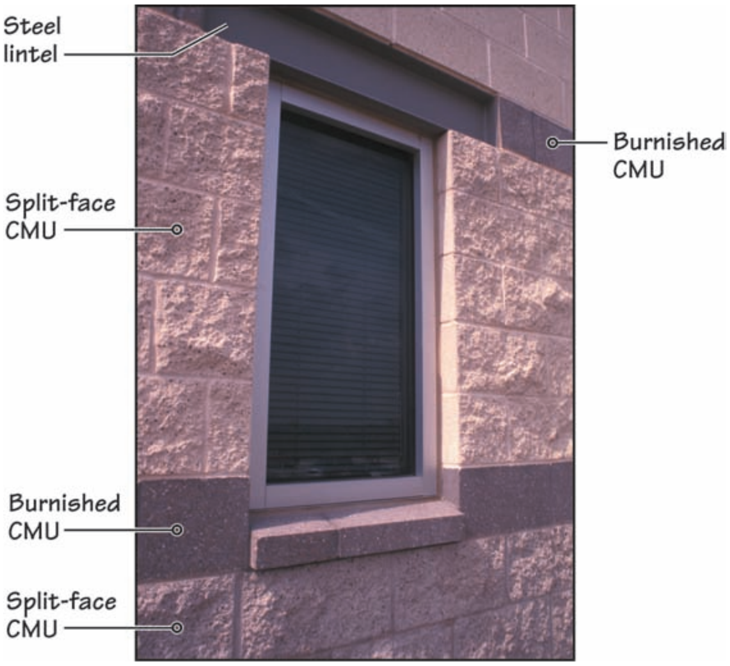

Steel lintel
Burnished CMU
Split-face CMU
Burnished CMU
Split-face CMU

FIGURE 25.11 Use of burnished units as accent bands in a split-face CMU wall.

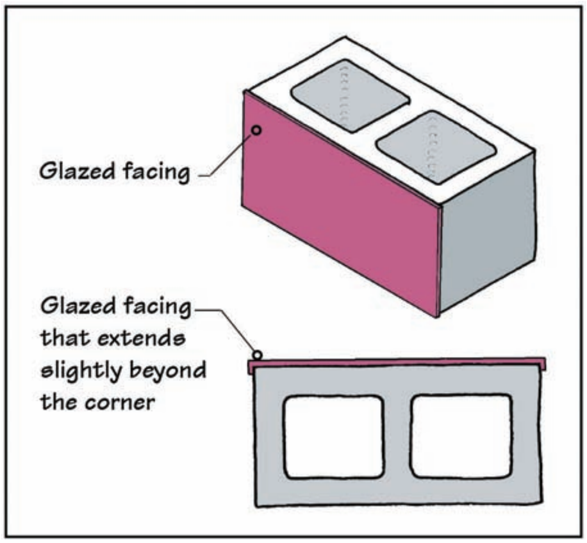

Glazed facing
Glazed facing that extends slightly beyond the corner

FIGURE 25.12 A glazed concrete masonry unit.

25.2 CONCRETE MASONRY UNITS—MANUFACTURING AND SPECIFICATIONS

CMUs are made from concrete. Therefore, a CMU-manufacturing plant has concrete-making equipment in addition to the equipment required to manufacture the units. Briefly, CMU manufacturing involves casting fairly dry (zero-slump) concrete mix in molds of the desired shape and compacting the concrete.

Because of the zero-slump concrete, a fresh-cast (green) CMU has adequate strength to be removed from the mold immediately. A CMU casting and compacting machine will generally produce three to four units in one pass, Figure 25.13. The green units travel on rollers to be stacked on a multistack cart. As the cart, generally mounted on wheels, gets filled, it is moved to a curing chamber, where the units undergo accelerated curing by warm (approximately 150°F), supersaturated air, Figure 25.14.

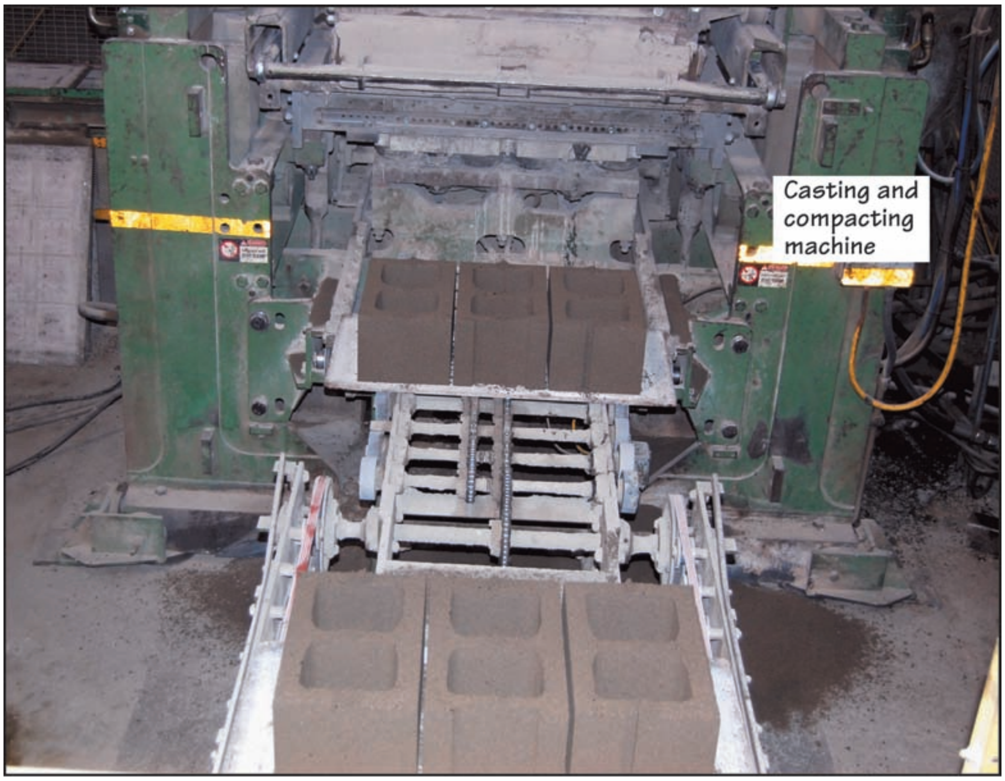

Casting and compacting machine

FIGURE 25.13 Fresh-cast (green) CMUs travel on rollers to be stacked on a cart that delivers them to the curing chamber (Figure 25.14).

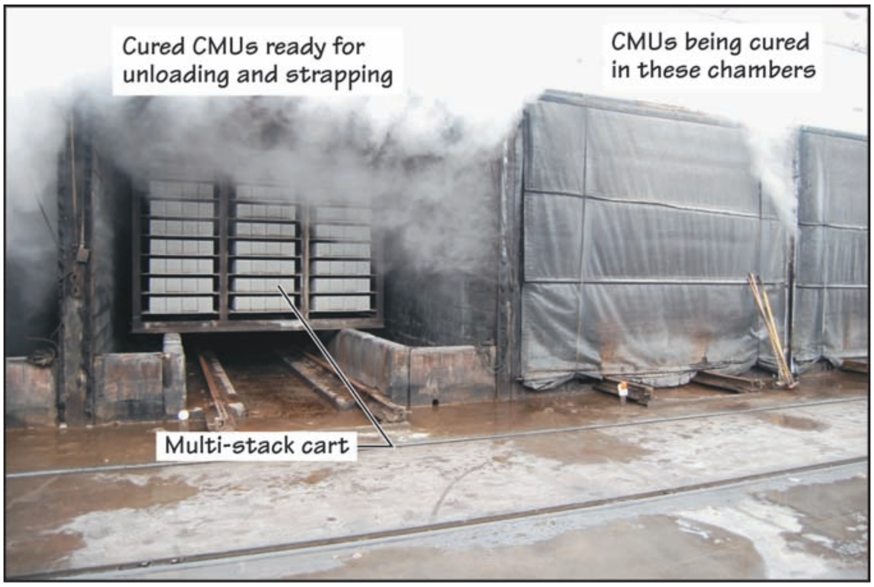

Cured CMUs ready for unloading and strapping
CMUs being cured in these chambers
Multi-stack cart

FIGURE 25.14 Curing chambers for accelerated curing of CMUs. Observe the warm saturated-air clouds. (The photograph was taken on a cold day; on a really warm day, clouds may not be visible.)

The units are cured (typically for 10 hours) and then unloaded from the multistack cart to wooden pallets, strapped into cubes, and stored in the yard for shipping to the construction site. Because the manufacturers do not want a large inventory in their storage yards, it is possible that a unit may be sent to the construction site within a day or two of being manufactured.

Specifications for CMUs

Virtually all shapes of CMUs can be made from lightweight or normal-weight concrete. A lightweight CMU is made from lightweight coarse aggregate, and normal-weight units are made from normal-weight coarse aggregate. The weight classification is based on the following concrete densities:

- *Lightweight CMU*—dry concrete density $<$105 lb/ft^3
- *Normal-weight CMU*—dry concrete density $\geq$125 lb/ft^3

A *medium-weight* unit is also made by some manufacturers, with a dry concrete density of 105 lb/ft3 to 125 lb/ft^3. A typical 8-in. (two-cell) lightweight unit weighs approximately 28 lb, and a normal-weight unit weighs approximately 38 lb. Lightweight units are preferred because they reduce the dead load on a structure, and they are easier to work with. The masons may charge less for laying them. However, because lightweight aggregate costs more (see Chapter 21), lightweight units are generally more expensive than normal-weight units.

Lightweight units have the necessary strength for most situations. Where high unit strength is needed, normal-weight units should be considered. In any case, the minimum compressive strength of a CMU used in load-bearing applications is 1,900 psi (based on the net bearing area of the unit).

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The voids in CMUs are called
a. voids.
b. cores.
c. cells.
d. frogs.
e. none of the above.

2. The nominal length of a typical CMU is
a. 18 in.
b. 16 in.
c. 12 in.
d. 8 in.
e. variable.

3. The nominal height of a typical CMU is
a. 18 in.
b. 16 in.
c. 12 in.
d. 8 in.
e. variable.

4. The nominal width (through-wall thickness) of a typical CMU is
a. 18 in.
b. 16 in.
c. 12 in.
d. 8 in.
e. variable.

5. A typical CMU has
a. one web.
b. two webs.
c. three webs.
d. four webs.
e. five webs.

6. A typical CMU has
a. one face shell.
b. two face shells.
c. three face shells.
d. four face shells.
e. five face shells.

(*Continued*)

PRACTICE QUIZ *(Continued)*

7. Which of the following CMU shapes is used to simulate a stack-bond wall, although the wall is, in fact, made with a running-bond pattern?
a. Lintel
b. Bullnose unit
c. Sash unit
d. Unit with projecting face shells
e. Scored unit

8. Which of the following CMU shapes has a rounded corner?
a. Lintel
b. Bullnose unit
c. Sash unit
d. Unit with projecting face shells
e. Scored unit

9. CMUs with projecting face shells can be used on both sides of a control joint in a wall. The other unit that is commonly used in the same situation is a
a. scored unit.
b. bullnose unit.
c. sash unit.
d. lintel unit.

10. Which of the following CMU shapes has a U-shaped profile in its vertical cross section?
a. Lintel unit
b. Bullnose unit
c. Sash unit
d. Unit with projecting face shells
e. Scored unit

11. Arching action occurs in a masonry wall with
a. a running-bond pattern.
b. a stack-bond pattern.
c. both (a) and (b).
d. neither (a) nor (b).

12. A lintel over an opening in all masonry walls is designed to carry the load from triangle-shaped superimposed masonry.
a. True
b. False

13. If a CMU wall is vertically reinforced at 16 in. on centers, which of the following units will you recommend for use in the wall?
a. A-unit
b. H-unit
c. Standard unit with three webs
d. Sash unit
e. Bond beam unit

14. If a CMU wall is vertically reinforced at 8 in. on centers, which of the following units will you recommend for use in the wall?
a. A-unit
b. H-unit
c. Standard unit with three webs
d. Sash unit
e. Bond beam unit

15. If a CMU wall is vertically reinforced at 24 in. on centers, which of the following units will you recommend for use in the wall?
a. A-unit
b. H-unit
c. Standard unit with three webs
d. Both (a) and (b)
e. Both (a) and (c)

16. The center-to-center spacing of vertical reinforcement in a CMU wall cannot be less than 8 in.
a. True
b. False

17. Which of the following CMUs has slotted webs that are broken before being laid in the wall?
a. A-unit
b. H-unit
c. Standard unit with three webs
d. Sash unit
e. Bond beam unit

18. The terms *pilaster* and *pier* are synonymous.
a. True
b. False

19. A split-face CMU is made by treating a standard CMU with an oxyacetylene torch to produce a very smooth surface on one or more faces of the unit.
a. True
b. False

20. A burnished CMU is made by treating a standard CMU with an oxyacetylene torch to produce a very smooth surface on one or more faces of the unit.
a. True
b. False

NOTE

Why Only Face-Shell Mortaring of CMUs?

1. When a wall bends, the tensile and compressive stresses are concentrated primarily at the front and back faces of the wall. Mortaring the webs, therefore, does not significantly increase a wall's bending strength.
2. Because CMUs are laid in running bond, the webs of a CMU in the upper course do not fully align with the webs of CMUs in the lower course. Therefore, if the mortar is placed on the webs, it will not serve any purpose. Additionally, not mortaring the webs speeds construction.

25.3 CONSTRUCTION OF A CMU WALL

The construction of a CMU wall differs from that of a brick wall in the following ways:

- Because a CMU is much heavier than a brick, it requires two hands to lay instead of the one-hand operation used in laying bricks, Figure 25.15. While it takes greater effort and time to lay a CMU than a brick because of a CMU's much larger size, the construction of a CMU wall is much faster.
- Unlike bricks, whose bed and head joints are fully mortared, a CMU is generally mortared only on its exterior periphery. The masonry industry refers to it as *face-shell mortaring* of the units, Figure 25.16. In face-shell mortaring, the webs of a CMU are not mortared. The exceptions are stack-bond walls and partially grouted CMU walls—mortaring the webs on both sides of a grouted cell in a partially grouted wall prevents the grout from flowing into ungrouted cells. The first course of a CMU wall is laid over a full bed of mortar regardless of the type of wall.
- A typical CMU wall contains joint reinforcement for shrinkage control, which is not required in brick walls other than a stack-bonded brick wall.
- A reinforced CMU wall is generally *partially grouted* because only cells that contain reinforcement need the grout. Other cells are left ungrouted unless fire-resistance and/or sound-insulation requirements mandate a *fully grouted* wall. A reinforced brick wall, on the other hand, must be fully grouted in all cases—the grout being provided in the space between two masonry wythes, Figure 25.17.

The images in Figure 25.18 highlight some of the similarities and differences between the construction of brick and CMU walls.

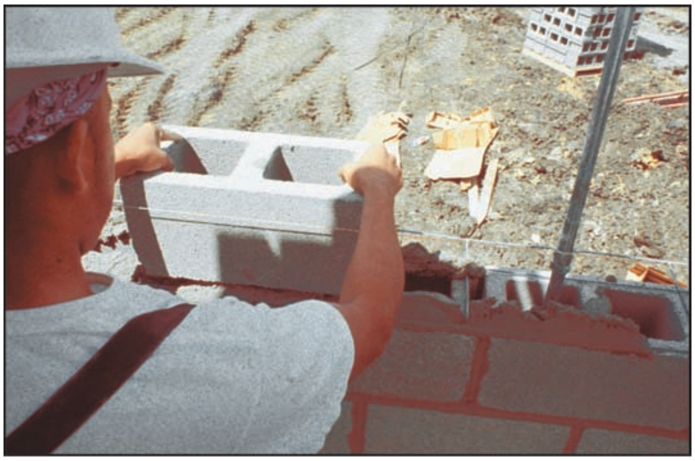


FIGURE 25.15 The laying of a CMU is a two-hand operation versus the one hand used in laying bricks.

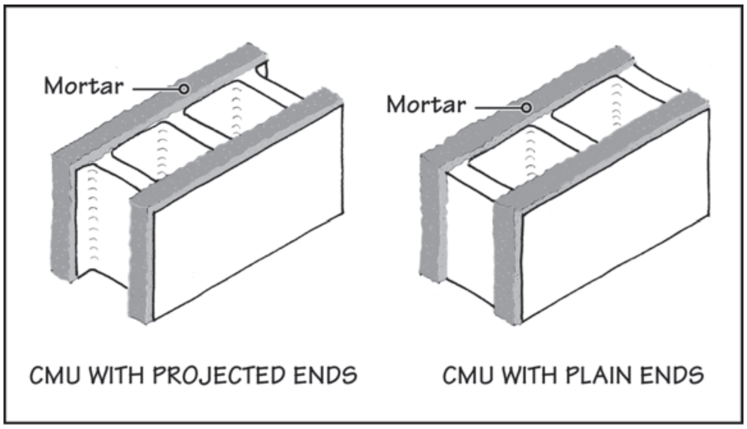

Mortar
Mortar
CMU WITH PROJECTED ENDS
CMU WITH PLAIN ENDS

FIGURE 25.16 In a CMU wall, only face shells are generally mortared; that is, the webs are not mortared, and the head joints are mortared to the depth of the face shells.

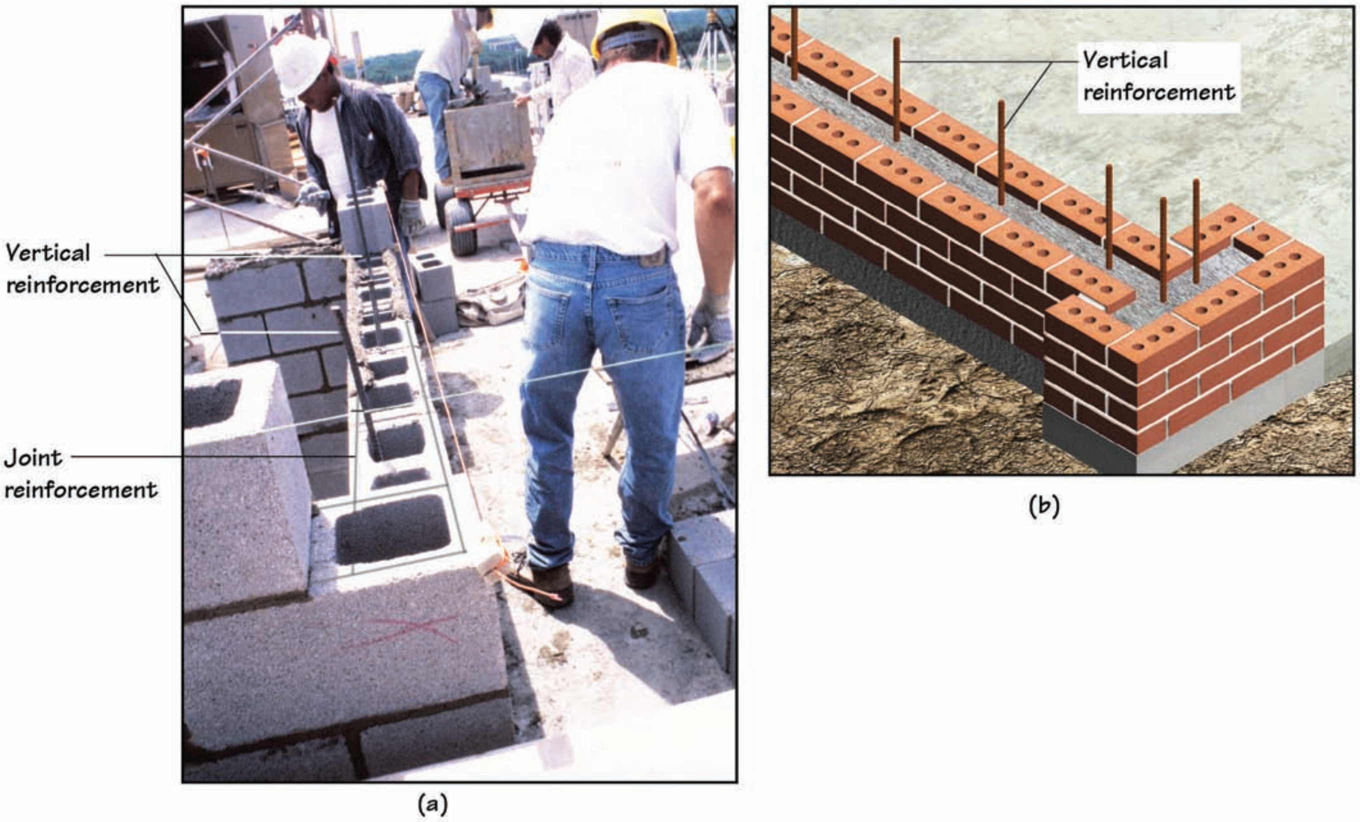

Vertical reinforcement
Joint reinforcement
(a)
Vertical reinforcement
(b)

FIGURE 25.17 **(a)** A CMU wall is called a *reinforced CMU wall* if it is provided with vertical steel reinforcement. Generally, only CMU cells with reinforcement are grouted. The other cells are left ungrouted, unless the grouting of unreinforced cells is required for greater fire resistance and (or) greater sound insulation of the wall. Note that in this photograph the CMU wall is reinforced 24 in. on center. Observe that the first CMU course is laid in full mortar bed. **(b)** A reinforced brick masonry wall must be fully grouted in the space between the two wythes of the wall.

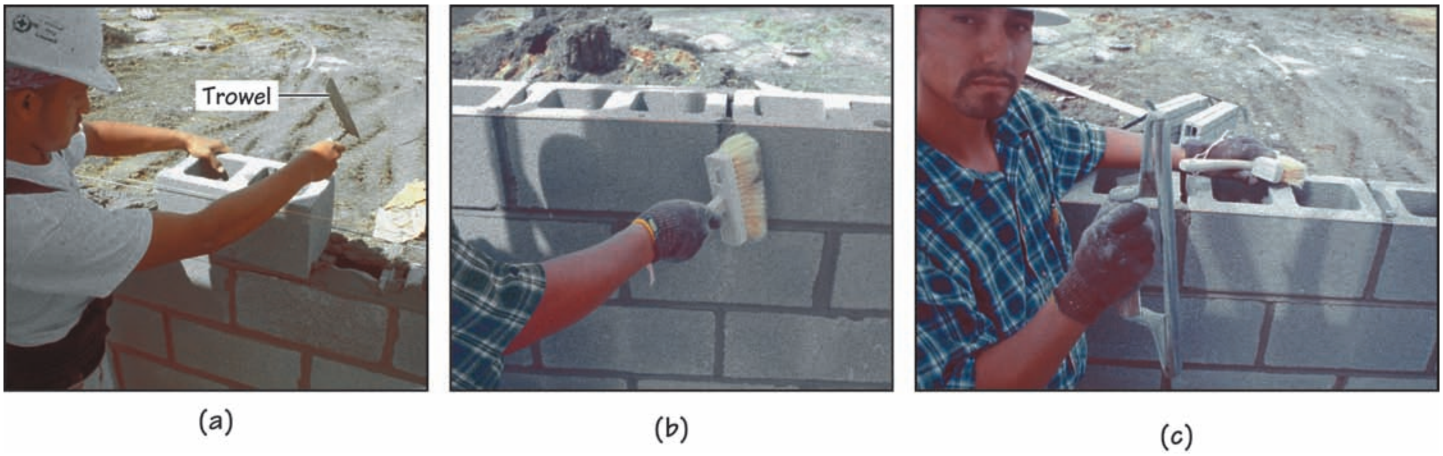


FIGURE 25.18 **(a)** The unit is aligned, and pressed downward and sideways using the trowel. **(b)** The mortar is brushed off the face of the walls when it has dried sufficiently. **(c)** The concave joint tool used with CMUs is longer than the one used with brick masonry (see Figure 24.28).

25.4 SHRINKAGE CONTROL IN CMU WALLS

As stated in Chapter 9, clay bricks expand during service, whereas CMUs shrink. As with concrete, the shrinkage of CMU continues for several months after their manufacture. Although ASTM specifications require that the manufacturers limit the maximum shrinkage potential of their units to the specified value, it is not economical to let CMUs stabilize their dimensions fully before selling them.

In other words, a CMU that arrives on the construction site may still be shrinking. Therefore, some shrinkage of units is to be expected after they are placed in the wall. Two means are employed to control the shrinkage of CMU walls:

- Providing horizontal reinforcement in the wall
- Providing control (shrinkage) joints so that a long CMU wall is divided into smaller segments

The purpose of horizontal reinforcement is to resist tensile stresses in the wall caused by the shrinkage of units. Note that horizontal reinforcement cannot prevent the formation of shrinkage cracks. Nor can it reduce the total width of cracks in a given length of a wall. However, reinforcement distributes the cracks in the wall by increasing their number and reducing the width of individual cracks—the total width of cracks remaining unchanged. Thus, instead of one or two large cracks, numerous small cracks are formed in the wall if horizontal reinforcement is provided. Small cracks are more water resistant, heal more easily, and can be sealed with a coating.

NOTE

Steel Wire Designation

A cold-drawn steel wire is designated by the cross-sectional area of the wire (see also Section 21.13). Thus, a W1.7 wire has a cross-sectional area of 0.017 in.^{2} (diameter = 0.147 in., or nearly $\frac{1}{7}$ in.). It is also referred to as *No. 9 gauge wire*.

A W2.1 wire has a cross-sectional area of 0.021 in.^{2} It is also referred to as *No. 8 gauge wire*. Some other commonly used wires are:

W1.1—gauge No. 11, area = 0.011 in.^{2}

W2.8—$\frac{3}{16}$-in. diameter, no gauge designation, area = 0.028 in.^{2}

W4.9—$\frac{1}{4}$-in. diameter, no gauge designation, area = 0.049 in.^{2}

HORIZONTAL REINFORCEMENT—JOINT REINFORCEMENT

Horizontal reinforcement is generally provided by steel wire reinforcement placed in the mortar joints, referred to as *joint reinforcement*. Joint reinforcement consists of two parallel longitudinal wires welded to cross wires. Two types of cross-wire arrangement are used, Figure 25.19.

- In *ladder-type joint reinforcement*, cross wires are perpendicular to the longitudinal wires.
- In *truss-type joint reinforcement*, cross wires are diagonal to the longitudinal wires.

As we will see in Chapter 28, both ladder- and truss-type reinforcement can have additional wires welded to it to tie a masonry veneer wall to a CMU backup wall. The longitudinal wires in joint reinforcement are embedded in the mortar. This is achieved by placing the joint reinforcement on the masonry bed and then placing the mortar over it, Figure 25.20. Because of face-shell mortaring, the cross wires are not covered by mortar.

The tensile stresses caused by the shrinkage of a CMU wall are resisted by the longitudinal wires. The cross wires simply hold the longitudinal wires together. The maximum permissible diameter of the longitudinal wires is half the mortar joint thickness (i.e., $\frac{3}{16}$ in.), but the smaller-diameter W1.7 wire (No. 9 gauge wire) is most commonly used.

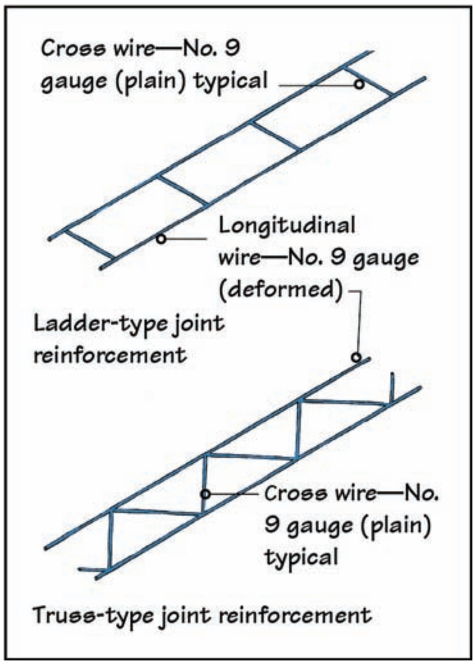

Cross wire—No. 9 gauge (plain) typical
Longitudinal wire—No. 9 gauge (deformed)
Ladder-type joint reinforcement
Cross wire—No. 9 gauge (plain) typical
Truss-type joint reinforcement

FIGURE 25.19 Types of joint reinforcement commonly used. Although 9-gauge wires are most common, other sizes are also available. The maximum permissible diameter of wire in joint reinforcement is half the mortar thickness.

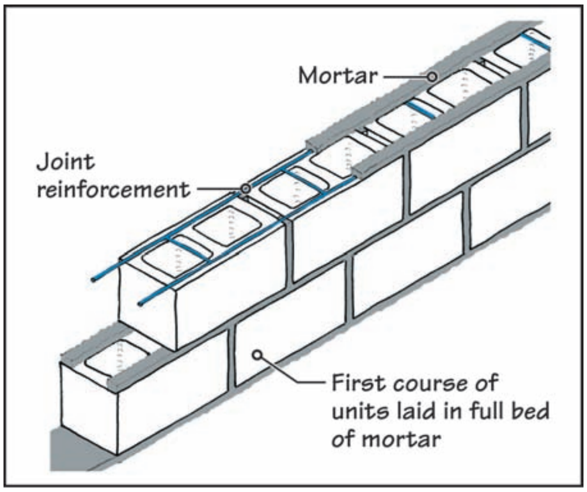


FIGURE 25.20 To embed joint reinforcement in mortar, standard practice is to place the joint reinforcement on the bed surface of the units first and then lay the mortar over it (see also Figure 25.17).

The longitudinal wires are slightly deformed (textured) to improve their bond with mortar. The cross wires (also No. 9 gauge) are generally plain, spaced no more than 16 in. on centers. Hot-dip galvanizing, in which the reinforcement is dipped in a hot bath of zinc, is required for corrosion protection. The thickness of galvanizing (zinc) film required depends on the exposure of the wall to corrosion. Where corrosion protection is critical, stainless steel joint reinforcement is recommended.

The fabrication of joint reinforcement (welding of cross wires with longitudinal wires and cutting to required lengths) should precede galvanizing. The alternative, in which the reinforcement is fabricated with galvanized wires, leaves the welded spots without any protection. If the latter is the mode of fabrication, the welded spots and sheared ends should be coated with zinc.

Joint reinforcement is generally available in 10-ft lengths. The distance between longitudinal wires has been standardized for CMU walls of different thickness. The standard requires that the longitudinal wires be spaced as far apart as possible. However, a minimum $\frac{5}{8}$-in. cover must be provided by the mortar, Figure 25.21. Therefore, for use in an 8-in. CMU wall, the out-to-out distance between wires is $(7\frac{5}{8} - \frac{5}{8} - \frac{5}{8}) = 6\frac{3}{8}$ in.

The vertical spacing of joint reinforcement in a wall is a function of the diameter of longitudinal wires and the thickness of the wall. With No. 9 gauge wires, the recommended spacing is 16 in. on center. This amounts to placing the joint reinforcement every other course of masonry. If $\frac{3}{16}$-in. longitudinal wires are used, the vertical spacing of joint reinforcement can be increased.

More stringent horizontal reinforcement requirements (wire diameter and vertical spacing of joint reinforcement) than those given here for shrinkage crack control may be needed to resist high-wind and seismic loads.

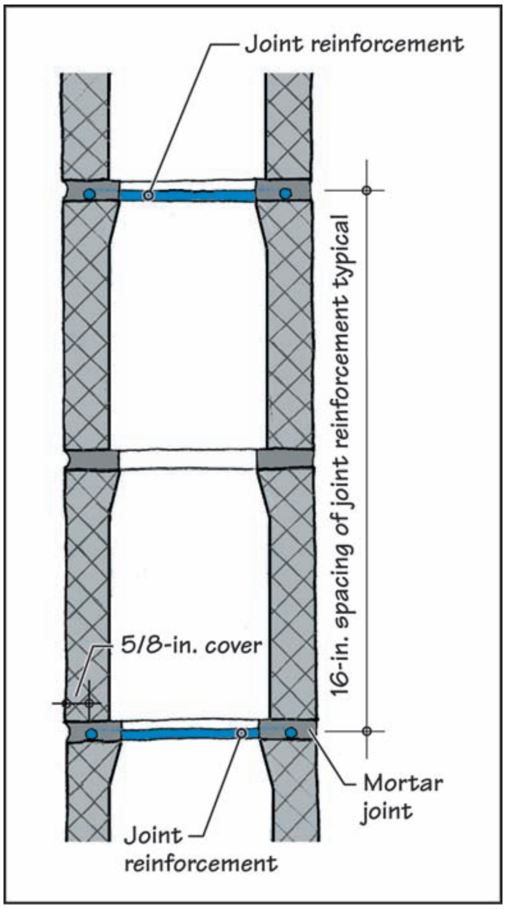


FIGURE 25.21 The width of joint reinforcement for CMU walls is standardized to provide $\frac{5}{8}$-in. mortar cover to longitudinal wires.

HORIZONTAL REINFORCEMENT—BOND BEAMS

Horizontal reinforcement in CMU walls may also be provided through bond beams. A bond beam is a CMU beam formed by grouting the bond beam units. The slotted webs of bond beam units are broken by the mason before being laid, providing a continuous space for horizontal reinforcement and grouting.

Because bond beam units are open at the top and the bottom, a plastic mesh fabric is placed below the units to prevent the grout from leaking into the lower cells. For shrinkage crack control, bond beams are generally spaced 4 ft on center vertically with only one No. 4 reinforcing bar ($\frac{1}{2}$-in. diameter) in each bond beam, Figure 25.22.

Bond beams are more cumbersome to provide than joint reinforcement. However, the reinforcement in a bond beam is better protected, and a bond beam can be reinforced more heavily to resist high-wind and seismic forces. As we will observe in Chapter 26, bond beams are required for reasons other than crack control in load-bearing masonry structures.

HORIZONTAL REINFORCEMENT AND STACK-BOND WALLS

A stack-bond wall is much weaker in horizontal bending than a running-bond wall because the continuous head joints open easily, presenting little resistance to horizontal bending, Figure 25.23(a). In a running-bond wall, the masonry units have to overcome the shear (sliding) resistance at the bed joints before the head joints can open, Figure 25.23(b).

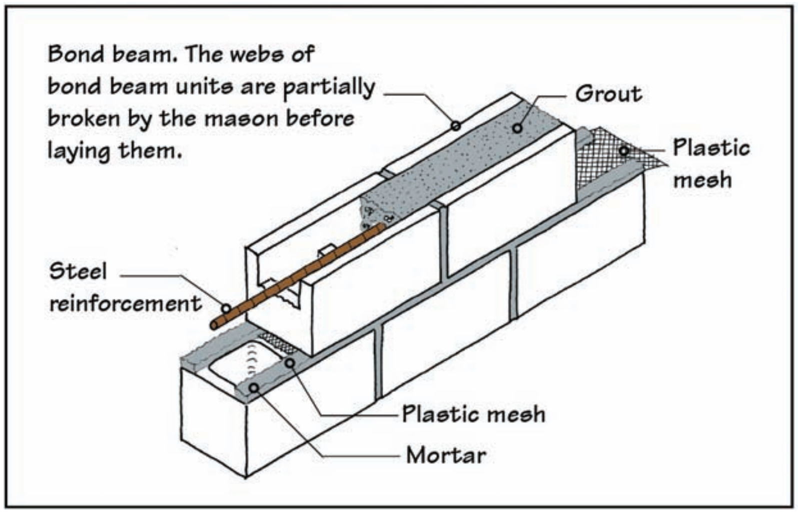
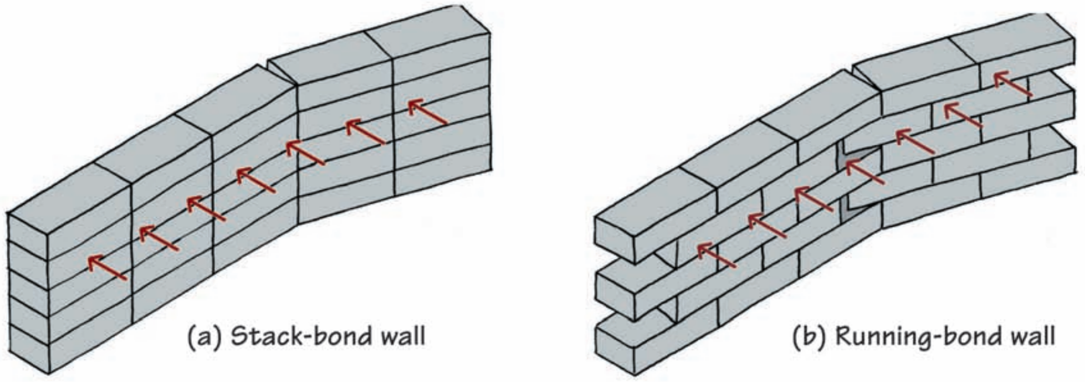

Bond beam. The webs of bond beam units are partially broken by the mason before laying them.
Grout
Plastic mesh
Steel reinforcement
Plastic mesh
Mortar

FIGURE 25.22 The use of bond beams for shrinkage crack control.



The horizontal bending strength of a stack-bond wall is only a function of the (flexural tensile) bond strength of head joints.

When a running-bond wall bends horizontally, the units must slide over the underlying units. The resistance of the units to sliding increases the bending strength of the wall. Note that this phenomenon is absent in a stack-bond wall.

The vertical bending strength of both a stack-bond and a running-bond wall is the same (see Figure 24.3). It can be increased by providing vertical reinforcement in walls (see Figure 24.4).

FIGURE 25.23 **(a)** The horizontal bending strength of a stack-bond wall is low because it is only a function of the flexural tensile bond strength of vertical joints. **(b)** The horizontal bending strength of a running-bond wall is greater than that of a stack-bond wall because of the shear (sliding) resistance provided by the units.

Horizontal reinforcement substantially increases the horizontal bending strength of a stack-bond wall. Tests have shown that if a CMU stack-bond wall is provided with joint reinforcement at 16 in. on centers, its bending strength is 20% greater than that of an unreinforced running-bond wall. If the running-bond wall is also reinforced horizontally in the same way as a stack-bond wall, both the stack-bond wall and the running-bond wall are equal in horizontal bending strength. Horizontal reinforcement in bond beams (4 ft on center) achieves the same result as joint reinforcement laid 16 in. on center.

CONTROL JOINTS

In addition to horizontal reinforcement, crack control in CMU walls requires the provision of continuous vertical control joints. The width of a control joint is usually the same as the thickness of a mortar joint—$\frac{3}{8}$ in. The recommendations for control joint spacing are as follows:

- The length-to-height ratio of a wall between control joints should be less than or equal to 1.5. In any case, the distance between control joints should not exceed 25 ft. Thus, if the height of a wall (from floor to floor or from floor to roof) is 10 ft, the maximum distance between control joints is 15 ft. However, if the wall height is 20 ft, the maximum distance between control joints is 25 ft.
- In addition to meeting the first provision, several other provisions should also be met, as shown in Figure 25.24.

The detailing of a control joint must ensure free horizontal movement of wall segments in addition to the transfer of the lateral load between adjacent segments. A typical control joint detail is shown in Figure 25.25(a). An alternative detail, which uses a sash unit on both sides of a control joint, is shown in Figure 25.25(b). A cross-shaped PVC gasket is used in sash unit recesses. The parts of the gasket within the sash units are required to have adequate hardness to function as shear key—to transfer the lateral loads across the joint.

25.5 GROUT

The purpose of masonry grout is to fill the voids in masonry walls so that the grout, the masonry units, and the reinforcement are integrated into a composite whole. Grout is, therefore, a cementitious mix, in many ways similar to concrete. Important differences between grout and concrete, however, do exist. For example, the durability of concrete is important, but this is not a concern with grout because it is protected by the units. A small amount of lime is permitted in grout but not in concrete.

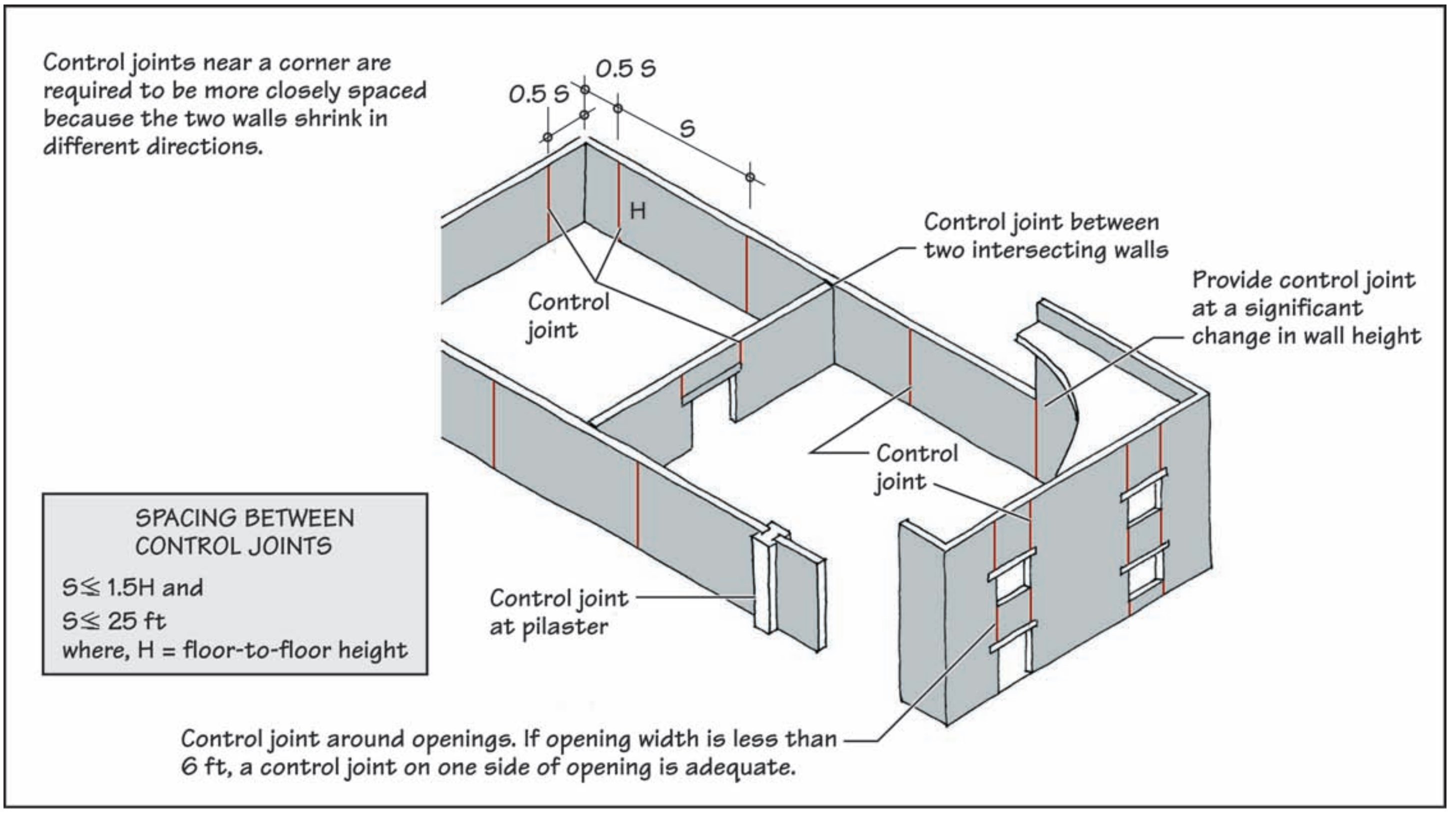

Control joints near a corner are required to be more closely spaced because the two walls shrink in different directions.
0.5 S
0.5 S
S
H
Control joint
Control joint between two intersecting walls
Provide control joint at a significant change in wall height
Control joint
SPACING BETWEEN CONTROL JOINTS
S≤ 1.5H and
S≤ 25 ft
where, H = floor-to-floor height
Control joint at pilaster
Control joint around openings. If opening width is less than 6 ft, a control joint on one side of opening is adequate.

FIGURE 25.24 Recommendations for control joint spacing in CMU walls.

Because grout is placed in masonry voids, it contains more water than concrete. In other words, grout is a "soupy" mix to allow it to flow down the voids, which are relatively small in size. The required slump of grout is 8 in. to 11 in., depending on the absorption characteristics of masonry units, void dimensions, and the ambient temperature and humidity conditions at the time of grout placement.

TYPES OF GROUT

Void dimensions also affect the type of aggregate used in grout. Grout is classified as *fine grout* and *coarse grout.* In fine grout, the aggregate consists of sand only. In coarse grout, the aggregate consists of sand and coarse aggregate. The maximum size of coarse aggregate is generally limited to $\frac{3}{8}$ in.

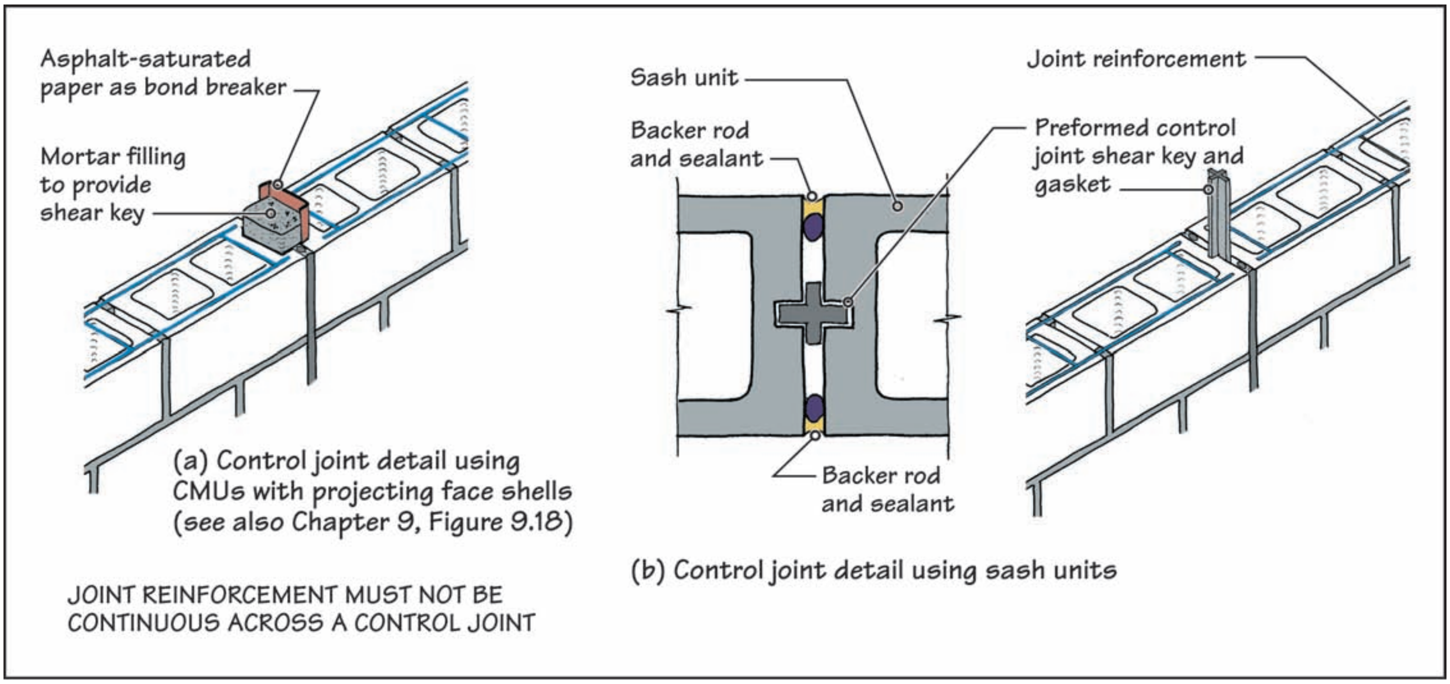

Asphalt-saturated paper as bond breaker
Mortar filling to provide shear key
(a) Control joint detail using CMUs with projecting face shells (see also Chapter 9, Figure 9.18)
JOINT REINFORCEMENT MUST NOT BE CONTINUOUS ACROSS A CONTROL JOINT
Sash unit
Backer rod and sealant
Backer rod and sealant
Preformed control joint shear key and gasket
Joint reinforcement
(b) Control joint detail using sash units

FIGURE 25.25 Two alternative details for control joints in CMU walls.

TABLE 25.1 PROPORTIONS OF MATERIALS IN A STANDARD GROUT MIX

		Proportions by Volume		
			Aggregate	
Grout type	Portland cement (PC)	Lime (L)	Fine	Coarse
Fine grout	1	$0\text{–}\frac{1}{10}$	2.25–3.0 times the sum of PC and L	—
Coarse grout	1	$0\text{–}\frac{1}{10}$	2.25–3.0 times the sum of PC and L	1–2 times the sum of PC and L

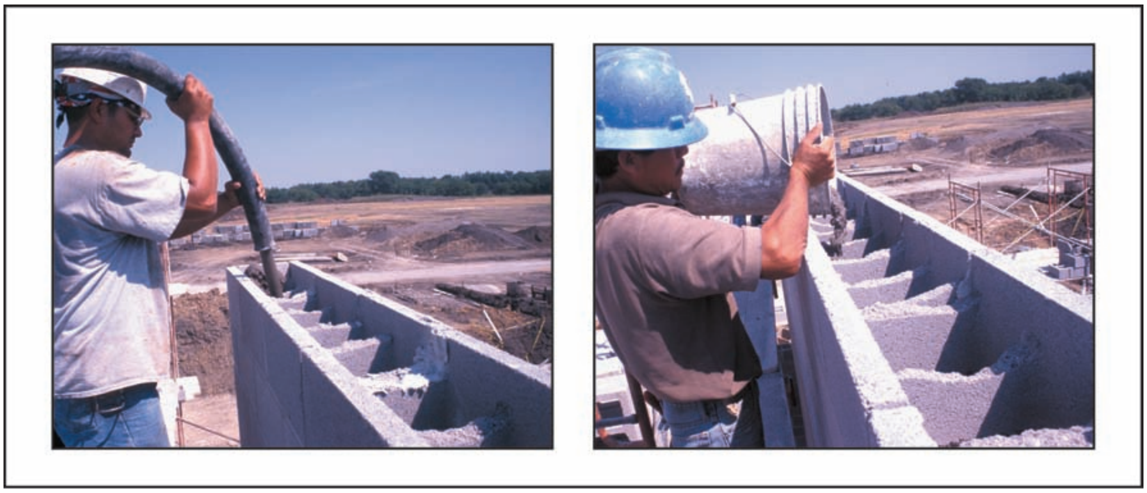


FIGURE 25.26 Two alternative methods of placing grout are pumping and bucketing. In these images, the masons are placing the grout in the cells of underlying CMUs. The CMUs showing at the top of the wall are bond beam units, which will be provided with horizontal reinforcement at a later date.

Fine grout is used where void dimensions are small. If void dimensions are large (greater than 1.5 in. × 3 in.), coarse grout is preferred because it shrinks less than fine grout. In any case, a shrinkage-compensating admixture may be specified for grout. Excess shrinkage (a result of the large slump of grout) can leave voids, reducing the bond between the units, the grout, and the reinforcement. Proper consolidation will, however, reduce shrinkage to some extent.

The compressive strength of grout must be at least equal to that of masonry but not less than 2,000 psi. The strength of grout is established by testing specimens after 28 days of casting them. As an alternative to testing, grout may be proportioned by the requirements in Table 25.1, which results in a grout with a compressive strength of approximately 2,500 psi.

Two methods are used to pour grout in masonry walls—pumping and bucketing, Figure 25.26. Pumping is more commonly used in a *high-lift grouting* operation. High-lift grouting is used where the entire height of the wall (up to a maximum of 24 ft) is grouted in one operation. Bucket placement is economical in small jobs or where *low-lift grouting* is specified. In low-lift grouting, the wall is grouted as it is constructed, generally up to 4 ft in height. Some architects and engineers prefer specifying low-lift grouting because it provides better quality control, particularly if the wall is heavily reinforced.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

21. In a typical CMU wall, face-shell mortaring is used. This implies that the mortar is placed
- **a.** only on the horizontal surfaces of the face shells.
- **b.** on the horizontal and vertical surfaces of the face shells.
- **c.** on the horizontal surfaces of the face shells as well as the webs.
- **d.** on the vertical surfaces of the face shells only.

22. The grouting of the cells of a CMU wall is required where
- **a.** the cells are provided with steel reinforcement.
- **b.** greater fire resistance of the wall is required.
- **c.** greater sound insulation of the wall is required.
- **d.** all of the above.
- **e.** both (a) and (b).

23. Joint reinforcement refers to
- **a.** the vertical reinforcement in a masonry wall.
- **b.** the horizontal reinforcement in a masonry wall.
- **c.** both vertical and horizontal reinforcement in a masonry wall.

24. Joint reinforcement in CMU walls generally consists of
- **a.** a single wire.
- **b.** two parallel wires connected together by cross wires.
- **c.** three parallel wires connected together by cross wires.
- **d.** two parallel wires without cross wires.
- **e.** none of the above.

PRACTICE **QUIZ** *(Continued)*

25. The primary purpose of joint reinforcement in a CMU wall is to
  - **a.** increase the compressive strength of the wall.
  - **b.** increase the shear strength of the wall.
  - **c.** absorb the compressive stress in the wall caused by the expansion of units.
  - **d.** absorb the tensile stress in the wall caused by the expansion of units.
  - **e.** absorb the tensile stress in the wall caused by the shrinkage of units.

26. Bond beams in a CMU wall can be used to serve the same purpose as joint reinforcement.
  - **a.** True
  - **b.** False

27. The spacing of control joints in a CMU wall
  - **a.** should not exceed 25 ft.
  - **b.** is a function of the length-to-height ratio of the wall.
  - **c.** is a function of the average annual air temperature of the location.
  - **d.** (b) and (c).
  - **e.** (a) and (b).

28. Masonry grout is a mixture of
  - **a.** Portland cement and water.
  - **b.** Portland cement, aggregate, and water.
  - **c.** Portland cement, lime, and water.
  - **d.** lime, aggregate, and water.
  - **e.** none of the above.

29. Masonry grout has a slump of approximately
  - **a.** 2 to 3 in.
  - **b.** 3 to 4 in.
  - **c.** 4 to 5 in.
  - **d.** 5 to 6 in.
  - **e.** none of the above.

30. Some architects and engineers prefer to specify low-lift grouting in masonry walls because
  - **a.** it is more economical.
  - **b.** it saves construction time and effort.
  - **c.** it does not require the use of coarse aggregate.
  - **d.** it does not require Portland cement.
  - **e.** none of the above.

25.6 NATURAL STONE

Natural stone is obtained from rocks that constitute the Earth's crust. Rock and stone are essentially the same materials, except that after the rock has been quarried, it is called *stone*. Stone that is used in buildings is called *building stone*. Clay and sand present on the Earth's surface are the result of the physical and chemical disintegration of rock by rainwater and air.

The term *dimension stone* refers to stone that has been fabricated to required dimensions, texture, surface finish, and so on, and meets performance requirements for durability, strength, water absorption, and the like. The term includes stone cladding panels, veneer stone, countertops and tabletops, wall copings, stair treads and risers, and balusters. It specifically excludes broken or crushed stone.

Stone is a natural material, so its characteristics (properties and appearance) are inconsistent. There is a great deal of variability even in slabs or blocks obtained from the same quarry pit. Stone is, therefore, too complex a material to describe with geological and chemical precision here. Fortunately, such precision is not only unnecessary but counterproductive, and this fact is recognized by the industry and ASTM standards.

The reason for discouraging excessive precision is that many building stones with different geological names have essentially the same performance characteristics. For example, gabbro, gneiss, basalt, and some other stones have virtually the same density, durability, abrasion resistance, and ability to accept polish as granite. So, these stones are referred to as the *granite group of stones*. While the geochemical distinction between them may be of interest to a geologist, it is unnecessary in commercial applications. Similarly, some stones, though geologically defined as limestone, are sold commercially as marble because, in their properties, they are closer to marble.

Building stones may be classified as follows:

- Granite or granite group
- Limestone and travertine group
- Marble or marble group
- Sandstone and quartzite group
- Slate

GRANITE OR GRANITE GROUP

Granite is an *igneous rock*. It is the strongest and densest of building stones. It weathers far more slowly than other stones and takes an extremely good polish. Therefore, it is commonly used in the exterior cladding of significant buildings.

Chemically, granite is a fusion of three minerals: feldspar (silicate of aluminum, calcium, sodium, and potassium), quartz (silicon dioxide), and mica (potassium aluminum silicate). These minerals are present as *granules*, which give granite its characteristic speckled surface appearance and name (*granite* from *granular*), Figure 25.27.

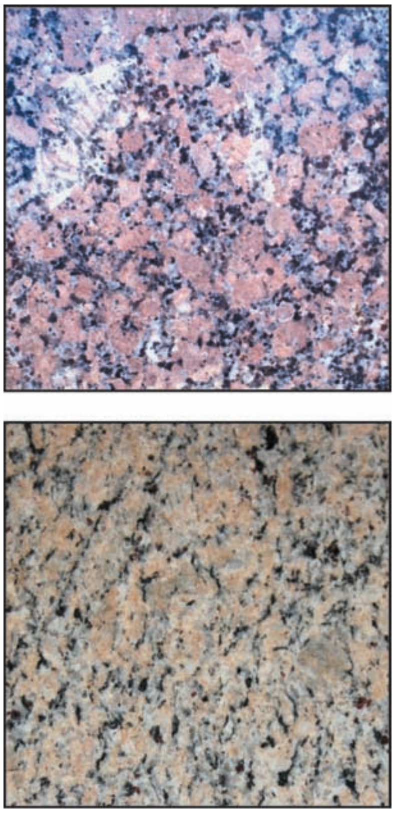


FIGURE 25.27 Speckled (granular) surface of granite.

EXPAND YOUR KNOWLEDGE

Geological Classification of Rocks

Geologists classify the rocks on the Earth's surface into:

- Igneous rock
- Sedimentary rock
- Metamorphic rock

As the Earth's crust began to cool from its original molten state to its present solid state, the first rock to form was igneous rock. In its molten form, the Earth's surface was essentially the same as the one that is present deep inside the Earth today. This molten rock, which is forced out during a volcanic eruption, is referred to as *lava* or *magma*.

The texture of *igneous rock* depends mainly on how slowly or rapidly the molten mass cooled. Slow cooling allowed the molecules to arrange themselves in crystals. If the molten mass cooled rapidly, the molecules did not have the time to arrange themselves in crystals. Thus, a rapidly cooled volcanic rock is noncrystalline (nongranular) and glassy—brittle and relatively weak.

The igneous rock that exists deeper inside the Earth's crust cooled rather slowly because of the insulating effect of the overburden. The coarse-grained crystalline structure of granite—an igneous rock—is the result of the slow cooling process that took place over thousands (millions) of years. The crystalline structure of granite gives it the hardness and strength for which it is well known.

Sedimentary rock began to form as the igneous rock disintegrated due to erosion by water. As the eroded particles were carried by water, many marine and other life forms were also carried with it. These substances were deposited in seas, lakes, valleys, and deltas and were compressed by the pressure of overlying material and bonded together, forming a different kind of rock, called *sedimentary rock*.

Limestone, travertine, and sandstone are sedimentary rocks. The difference between them is the chemical composition of the sediment beds and the material that cemented the beds. Limestone and travertine consist primarily of calcium carbonate. Sandstone consists of silicon dioxide.

Metamorphic rocks originate from either igneous or sedimentary rock that was altered (morphed) in its chemical structure by the action of heat and pressure. Marble, quartzite, and slate are metamorphic rocks. Marble is morphosed from limestone; quartzite, from sandstone; and slate, from shale. Because of the action of pressure and heat, a metamorphic rock is generally stronger than the rock from which it originated.

Chemical Classification of Rocks

In terms of their chemistry, rocks may be classified as:

- Siliceous rocks
- Calcareous rocks
- Argillaceous rocks

Siliceous rocks (such as sandstone, quartzite, and granite) are rich in silica (silicon dioxide). Calcareous rocks (such as limestone, marble, and travertine) are rich in calcite (calcium oxide). Argillaceous rocks (such as slate) are rich in alumina (aluminum oxide). Calcareous rocks are generally more prone to disintegration by acids but are slightly more fire resistive than siliceous rocks.

In general, granite contains 25% to 40% quartz and 3% to 10% mica; the remainder (50% or more) is feldspar. The relative proportions of these minerals and the size of their granules determine the strength, color, and surface appearance of granite. Quartz is the strongest and most durable of the three minerals. Therefore, a greater amount of quartz gives a stronger and harder granite that is more difficult to process—sawing, profiling, and grinding.

Being silicon dioxide, quartz is chemically the same as sand and, hence, is white to light pink in color. A granite low in quartz is generally darker in color. Commercial black granite is extremely low in quartz, approaching 0%, and is really not granite, but a stone called *basalt* by geologists. Black granite (basalt), which has a handsome finish, is commonly used as tabletops or countertops. Being relatively weaker, it is not favored for use where high strength or abrasion resistance is necessary, such as on floors and stair treads.

Both feldspar and mica present weakness in granite, particularly mica, because it decomposes more easily. Quartzite, a stone that is almost 100% quartz, is extremely strong. It is commonly used as an aggregate for ultra-high-strength concretes.

LIMESTONE

Limestone is a *sedimentary rock*, consisting primarily of the carbonates of calcium and magnesium, with small amounts of clay, sand, and organic material, such as seashells and other fossils. Limestone consisting of approximately 95% calcium carbonate and 5% impurities is called *calcite limestone*. That consisting of 60% to 80% calcium carbonate and 20% to 40% magnesium carbonate is called *dolomitic limestone*. Dolomitic limestone is generally stronger than calcite limestone.

Unlike granite, limestone is generally nongranular, with a relatively uniform surface appearance. It is softer than both marble and granite and hence easier to quarry, saw, and shape. It ranges in color from white to gray and does not take a polish.

Calcium carbonate reacts with acids. Acid in some foods (citric acid in lemons, limes, oranges, etc., and acetic acid in vinegar and pickles) reacts with limestone. That is why limestone is not recommended for use as kitchen, dining, or bar tabletops. Limestone facades in areas with serious acid rain problems have deteriorated. However, because acid rain is a relatively recent problem (related primarily to emissions from the use of petroleum and coal), the deterioration of limestone is also a recent problem.

Several historic buildings with limestone facades have performed quite well in the absence of reactive atmospheres, including the Empire State Building and Rockefeller Center in New York City, the Pentagon in Washington, D.C., and the Chicago Tribune Tower in Chicago, Illinois. Limestone is also commonly used as concrete aggregate.

TRAVERTINE

Travertine is a *sedimentary rock* obtained from the sediments of limestone dissolved in springwater. Springwater (particularly from hot springs) running over limestone deposits dissolved the limestone, which subsequently sedimented (i.e., were deposited) in a nearby location. Sometimes the sediment trapped water, which eventually evaporated, leaving voids in the rock. Travertine is, therefore, a porous stone, and travertine slabs are pitted with voids.

Travertine is closely related to limestone, but because it did not morph (change) like marble, it is a softer stone. Most travertine varieties, therefore, do not take a polish. Denser varieties, which take a good polish, are referred to as *travertine marble*.

Because of its porous structure, travertine does not have the durability required for use in thin slabs for exterior cladding. However, architects, who like the surface texture created by the pits, have used travertine in building exteriors as (thick) masonry walls. When travertine is used as a flooring material, its pitted surface can collect dirt, requiring greater maintenance unless the pits are filled with a Portland cement (or an epoxy) and ground smooth.

MARBLE

Geologically, marble is different from limestone because it is a *metamorphic rock*. Chemically, however, marble is similar to limestone. In fact, marble is limestone, which under centuries of high pressure and heat in the Earth's crust morphed from a sedimentary rock to a metamorphic rock.

Because of the pressure and heat, marble is stronger and denser than the original limestone but weaker than granite. Like granite, it takes a good polish. As stated previously, denser varieties of limestone that accept polish are sold (and used) commercially as marble.

Marbles vary in surface appearance, which can be without patterns or with patterns—veiny, or mottled, or both, Figure 25.28. The presence of veins often indicates the presence of faults, weakness, or cracks in marble. The use of veiny and variegated marble is generally discouraged for exterior applications. Marbles vary greatly in color—from white to black, pink, and so on. Being chemically identical to limestone, marble is also vulnerable to acid attack.

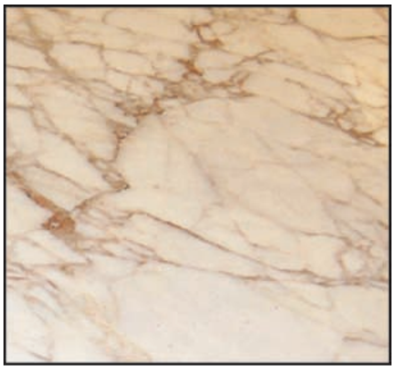


FIGURE 25.28 Veiny surface of marble.

SANDSTONE

Sandstone is a *sedimentary rock* formed by layers of sand (quartz) particles with oxides of calcium, silicon, and iron as cementing agents. If the cementing agent consists primarily of the oxide of silicon, sandstone is light in color and strong. If cemented by iron oxide, the sandstone is brown or red in color and softer. Sandstone that has a large amount of calcium oxide as cement is relatively more vulnerable to disintegration.

SLATE

Slate is a *metamorphic rock* formed by the morphosis of clay and mica sediments. Slate has a nongranular, smooth texture and is characterized by distinct cleavage planes that permit easy splitting in slabs as thin as $\frac{1}{4}$ in. That is why slate is used as roofing and flooring material. It is available in various colors, ranging from black to pink and light green.

25.7 FROM BLOCKS TO FINISHED STONE

Natural stone is procured by stone fabricators from quarries in the form of large blocks. Because of the way they are extracted from the rocks, blocks are irregular in size, Figure 25.29. The blocks are converted into slabs and other cross-sectional profiles in stone-fabrication plants. The conversion is done by sawing the blocks—a process similar to sawing lumber, except that water is used continuously during the sawing process to keep the saw blades cool, Figure 25.30.

The saw shown in Figure 25.30 uses one reciprocating blade that moves both horizontally and vertically so that only one slab is sliced at a time. In more sophisticated machines, several saw blades are ganged together to make multiple cuts in one pass.

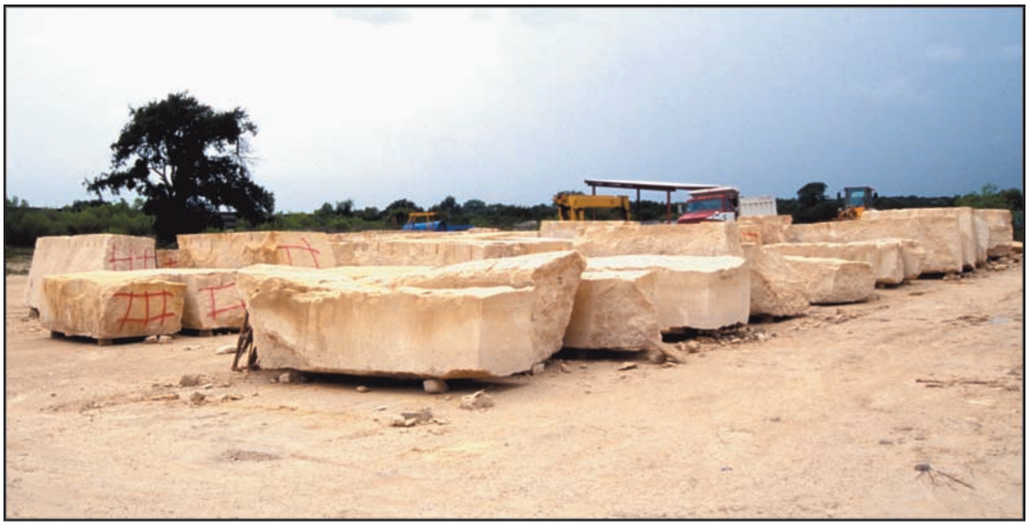


FIGURE 25.29 Blocks of stone outside a stone-fabricating plant.

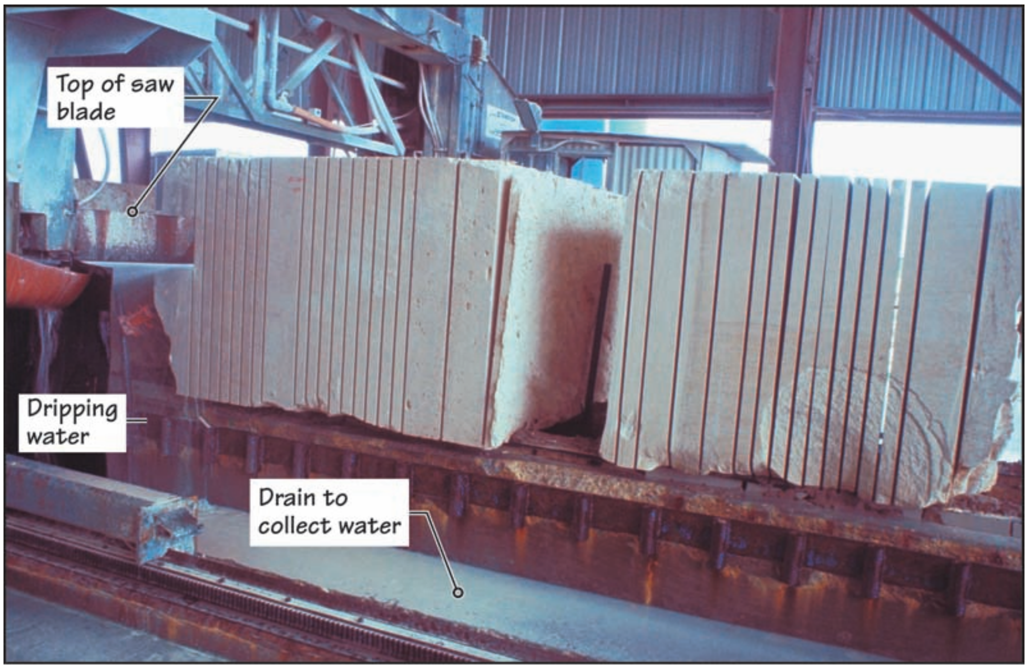


FIGURE 25.30 Conversion from stone blocks to slabs through sawing. Note that the sawing operation needs a great deal of water to cool the blade.

Cross-sectional profiles for round columns, column caps, balusters, wall copings, window sills, and so on, are obtained by machining the sawn material to the desired shape. Different types of power-driven tools or tool attachments are available for different profiles. Although most stone fabrication is automated, complex ornamental work requires working with hand tools such as chisels, picks, and hammers, Figure 25.31.

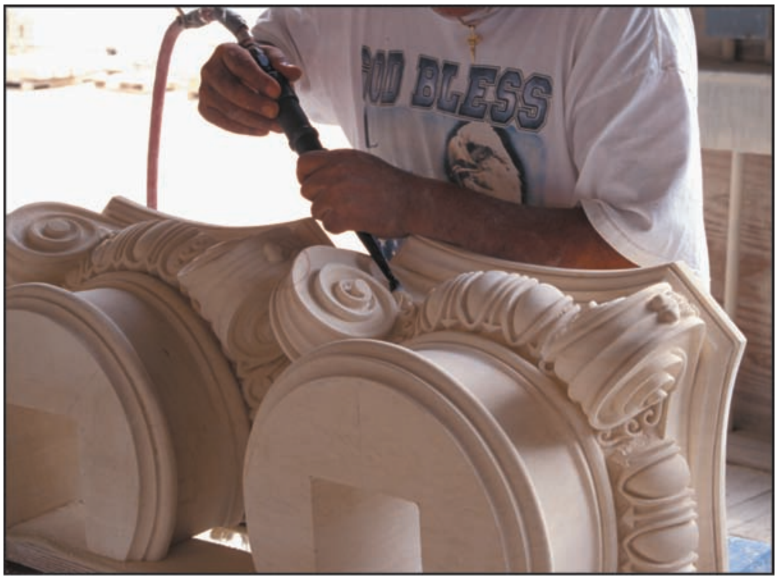


FIGURE 25.31 While a great deal of stonework is done through machines, some detailing requires working with hand tools.

FINISHES ON STONE SLABS AND PANELS

The surfaces of stone slabs and panels can be finished in several ways. The finish affects not only affects the surface appearance of the stone but also its durability. A honed or polished finish is generally more durable because it facilitates the drainage of water from the surface. The following are some of the commonly used finishes on stone slabs and panels:

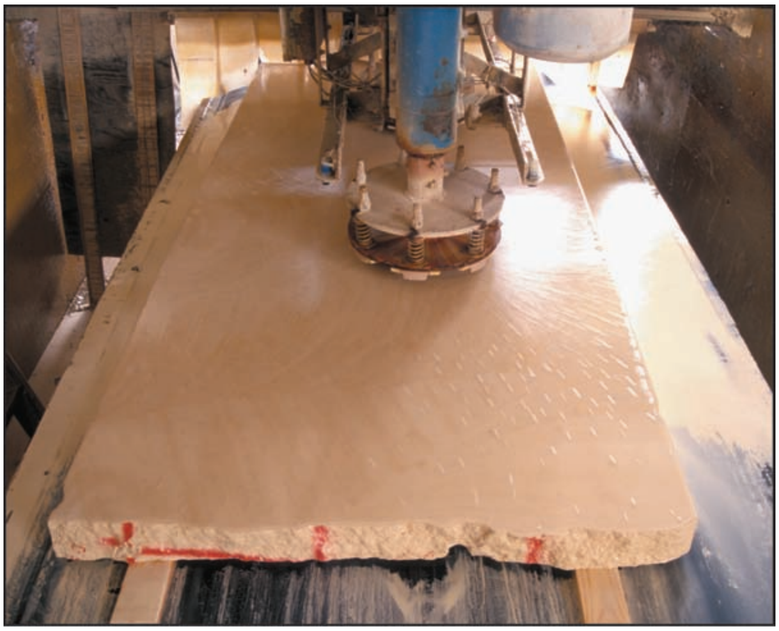


FIGURE 25.32 Honing (grinding) of stone slabs using water to cool the grinders.

- *Sawn finish:* If the stone is not finished beyond sawing, the surface is called a *sawn finish*. A sawn finish has visible saw marks.
- *Honed finish:* When a sawn finish is ground smooth with an abrasive material, a honed finish is obtained. Honing requires repeated grinding with increasingly fine abrasives. Water is used continuously during the honing process to control dust, Figure 25.32.
- *Polished finish:* Conceptually, there is no difference between a honed and a polished finish. A honed finish is smooth but with a matt appearance. A polished finish is obtained by grinding the stone surface beyond the honed finish with finer abrasives and finally buffing it with felt until the surface develops a sheen. A polished finish brings out the color of stone to its fullest extent by reflecting light like a mirror. The difference in color of a rough and a polished finish on the same stone is easily noticeable, often significant.

  A clear penetrating sealer that adds to the sheen is generally applied to the surface of a polished stone. The sealer increases the durability of stone by sealing the pores, adding resistance to chemical attack and the formation of stains. Only dense stones, such as granite, marble, and dense varieties of limestone, travertine, and slate, can develop a polish.
- *Flame-cut finish:* A flame-cut finish, also referred to as a *thermal finish*, is a rough finish obtained by torching the stone surface with a natural gas or oxyacetylene torch. Before torching, the stone is thoroughly wetted. The heat from the torch expands the absorbed water into steam, which breaks loose the surface particles in the stone, leaving behind a rough surface. Generally, a flame-cut finish is used only on granite because other stones are too porous to break only at the surface.

  The roughness of a flame-cut finish makes it ideal for floors, particularly those that are subject to frequent wetting. Often, a flame-cut finish is used in the treads of granite-topped stairs and a polished finish is used for the risers, which gives the desired contrast between the treads and the risers.
- *Bush-hammered finish:* A bush-hammered finish is also a rough finish and is obtained by hammering off the surface of stone with picks.
- *Split-face (cleft) finish:* Like a CMU, stone can also be split through one of its faces, yielding two split-face slabs. Splitting is easier in slate, which has natural cleavage planes, in which case the stone is referred to as *cleft-finished*. In the stone industry, however, the terms *cleft* and *split-face* are used interchangeably.
- *Sandblasted finish:* Although not as commonly used as other finishes, sandblasting stone yields a rough surface.

25.8 STONE SELECTION

The selection of stone for a particular use is a function of several factors. Budget and aesthetics (color, pattern, and surface appearance) are the two most important factors to be considered for stone used in building interiors. For exterior use, the performance history of a stone in the local environment (durability) is obviously another important factor. Where the material has no track record, the physical properties of the stones being evaluated should be compared. Generally, the following properties are of importance:

- Density
- Water absorption

EXPAND YOUR KNOWLEDGE

Granite versus Marble

Of the various building stones, granite and marble are the most important. Both are dense, strong stones and take a good polish. In many buildings, the final choice of stone for a particular application is between granite and marble.

Both granite and marble have their own beauty and individual personalities. In most situations, the selection is based on personal preference, cost, and availability. Marble comes in a much wider range of colors than granite and offers interesting veins. Veins are streaks of a different color than the main body of marble—much like the grain in wood (Figure 25.28). Veins may be streaks of weakness and cracks. Marble is commonly used for bathroom countertops and walls.

Granite is also available in many colors, and its surface is spotty and speckled. Because of its hardness, it can better withstand scratch damage from kitchen knives and utensils than any other stone. Abrasion resistance and resistance to acids make granite most suited for kitchen countertops and exterior cladding. Its high density and low water absorption further add to its durability, particularly against freeze-thaw action.

Marble also performs well in exterior cladding and has been used extensively for centuries. However, because of the availability of more sophisticated tools that allow a strong, dense stone like granite to be easily machined to profiles, granite is replacing marble for the cladding of significant buildings.

Both marble and granite are suitable for the cladding of interior walls and interior floors.

TABLE 25.2 COMMON APPLICATIONS OF SELECTED STONES

Application	Commonly used stones
• Exterior wall cladding	Granite, marble, and limestone
• Interior wall cladding	Granite, marble, and limestone
• Interior flooring	Granite, marble, and slate
• Stair treads and risers	Granite
• Kitchen countertops	Granite
• Bathroom countertops	Granite and marble
• Wall copings and balusters	Granite, marble, and limestone
• Roofing	Slate

- Compressive strength
- Flexural strength (modulus of rupture)
- Abrasion resistance

Of these properties, density and water absorption are the most important because they affect the durability of stone against freeze-thaw and chemical attack. Abrasion resistance is important in floors, but it is generally related directly to density. Flexural strength of stone is important in wall-cladding applications. Stone quarries and/or stone suppliers provide the required data for their stones.

Table 25.2, based on common uses of various stones, provides a rough guide in stone selection.

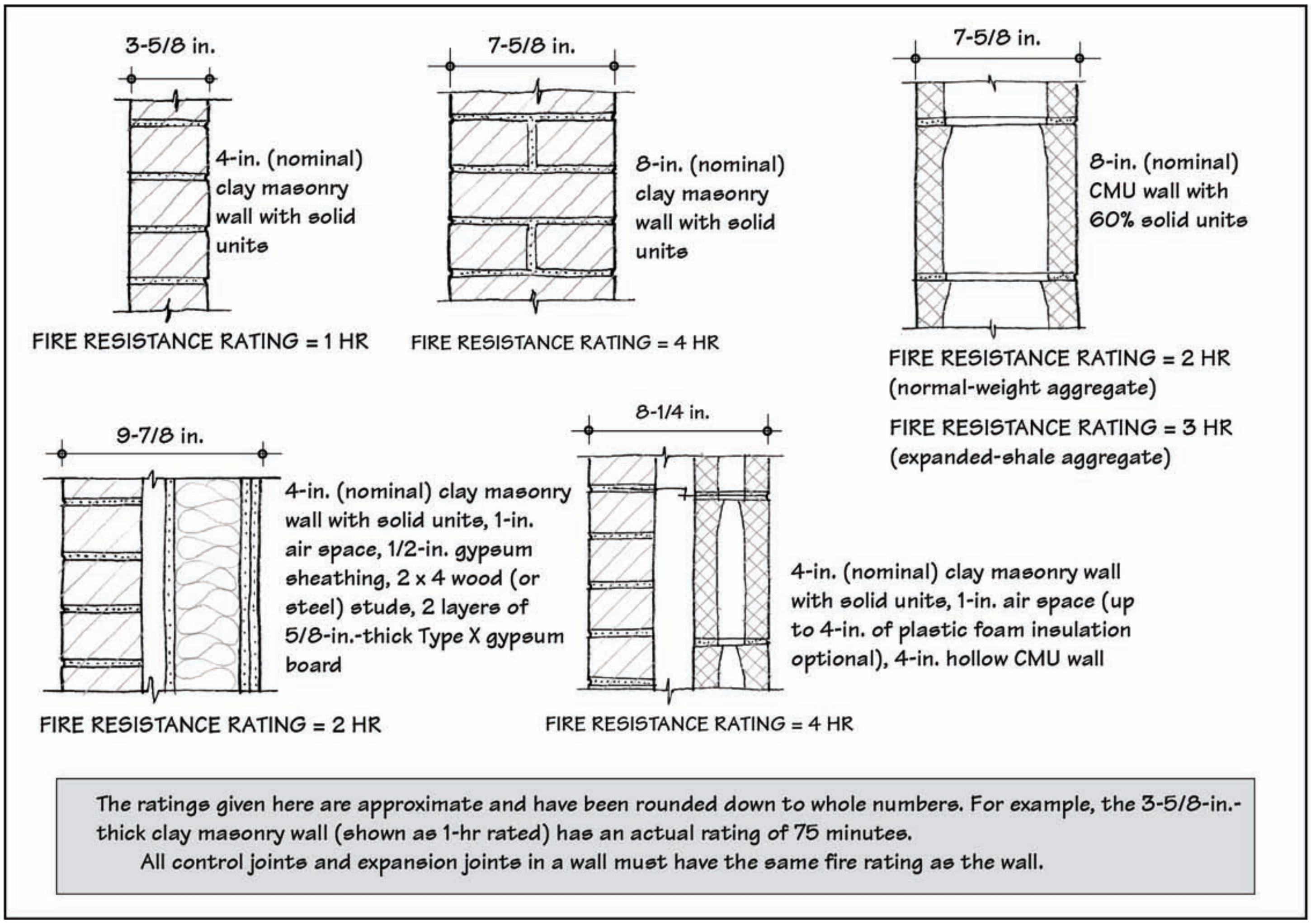
25.9 FIRE RESISTANCE OF MASONRY WALLS

Fired clay, concrete, and stone are noncombustible and inherently fire enduring. Therefore, the fire-resistance ratings of masonry assemblies are generally high. One of the important factors that affects the fire-resistance rating of a masonry wall is the amount of solid content in them. The greater the solid content, the greater the fire-resistance rating of a wall. Therefore, a grouted masonry wall has a higher fire-resistance rating than an ungrouted wall.

Because CMUs are generally hollow, the fire resistance rating of a CMU wall is given in terms of the wall's equivalent (solid) thickness. *Equivalent thickness* is the thickness of the wall excluding the cells (voids). Thus, if a wall is made of $7\frac{5}{8}$-in.-thick (8-in. nominal) units that are 60% solid (40% hollow), the wall's equivalent thickness is $7.625(0.6) = 4.575$ in. Note that $7\frac{5}{8} = 7.625$, and 40% hollow means 60% solid. The equivalent thickness of a fully grouted wall is the thickness of the wall itself.

Another factor that influences the fire-resistance rating of a CMU wall is the type of aggregate used in CMUs. A wall made with CMUs containing lightweight aggregate gives a higher fire-resistance rating for the same equivalent thickness than a wall with CMUs containing normal-weight aggregate.

Figure 25.33 gives the approximate fire-resistance ratings of selected masonry assemblies. For design purposes, more authoritative publications should be referenced. A comprehensive reference is that published by the Underwriters' Laboratories (UL). Another good source is the International Building Code.


3-5/8 in.
4-in. (nominal) clay masonry wall with solid units
FIRE RESISTANCE RATING = 1 HR
7-5/8 in.
8-in. (nominal) clay masonry wall with solid units
FIRE RESISTANCE RATING = 4 HR
7-5/8 in.
8-in. (nominal) CMU wall with 60% solid units
FIRE RESISTANCE RATING = 2 HR (normal-weight aggregate)
FIRE RESISTANCE RATING = 3 HR (expanded-shale aggregate)
9-7/8 in.
4-in. (nominal) clay masonry wall with solid units, 1-in. air space, 1/2-in. gypsum sheathing, 2 x 4 wood (or steel) studs, 2 layers of 5/8-in.-thick Type X gypsum board
FIRE RESISTANCE RATING = 2 HR
8-1/4 in.
4-in. (nominal) clay masonry wall with solid units, 1-in. air space (up to 4-in. of plastic foam insulation optional), 4-in. hollow CMU wall
FIRE RESISTANCE RATING = 4 HR

The ratings given here are approximate and have been rounded down to whole numbers. For example, the 3-5/8-in.-thick clay masonry wall (shown as 1-hr rated) has an actual rating of 75 minutes.

All control joints and expansion joints in a wall must have the same fire rating as the wall.

FIGURE 25.33 Approximate fire-resistance ratings of selected masonry walls.

FOCUS ON SUSTAINABILITY

Sustainability Features of Masonry

The most important sustainability feature of masonry is its durability. Masonry structures can stand and remain serviceable for a very long time, requiring little maintenance. Their durability is a result of several factors. First, they degrade slowly because they are resistant to physical, biological, and chemical deterioration. Second, they are noncombustible. The following are additional sustainability features of masonry:

Local production: Clay masonry units and CMUs are generally produced in most communities.

Reusability: Masonry materials can be easily reused. Salvaged bricks and stones are available in most communities. Some owners and architects prefer to use salvaged masonry. Interlocking concrete masonry pavers or units used in retaining walls do not require any mortar and can be disassembled and reused.

Recyclability: Masonry materials can also be easily recycled. Crushed and pulverized bricks (referred to as *grog)* can be mixed with clay and used to manufacture new bricks. Stone can be used as aggregate for concrete, and crushed CMUs can be used as underbed for concrete footings and slabs-on-grade.

Absence of VOC emissions: Masonry materials do not emit any volatile organic compounds (VOCs). Although radon gas has been associated with certain soils, brick manufacturers ensure the absence of radon in the clay used in the manufacture of bricks.

Thermal mass: All masonry materials provide thermal mass, which may help conserve energy in some climates (see Chapter 5).

Embodied energy: The embodied energy in stone and CMUs is lower than that in clay brick, which in turn has much lower embodied energy than metal or glass.

Negative sustainability aspects of masonry include soil erosion and habitat loss caused by the mining of clay and stone. However, like the other industries, the masonry industry is becoming increasingly aware of its responsibilities to the environment. Brick manufacturers are increasingly converting abandoned pits into lakes for use by the community.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

31. Geologically, the earliest rock on the Earth's surface was
- **a.** an igneous rock.
- **b.** a sedimentary rock.
- **c.** a metamorphic rock.
- **d.** none of the above.

32. Marble is
- **a.** an igneous rock.
- **b.** a sedimentary rock.
- **c.** a metamorphic rock.
- **d.** none of the above.

33. Granite is
- **a.** an igneous rock.
- **b.** a sedimentary rock.
- **c.** a metamorphic rock.
- **d.** none of the above.

34. Slate is
- **a.** an igneous rock.
- **b.** a sedimentary rock.
- **c.** a metamorphic rock.
- **d.** none of the above.

35. Which of the following stones is generally more vulnerable to disintegration by an acidic atmosphere?
- **a.** Granite
- **b.** Marble

36. In general terms, which of the following stones is considered most durable?
- **a.** Marble
- **b.** Granite
- **c.** Limestone
- **d.** Sandstone
- **e.** Slate

REVIEW QUESTIONS

1. Explain the differences between lightweight and normal-weight CMUs, including their uses.
2. Explain why CMUs are generally face-shell mortared. In which situations is full-bed mortaring of CMUs used?
3. Explain the purpose of joint reinforcement in CMU walls. Sketch a typical joint reinforcement used in CMU walls.
4. With the help of sketches, explain why a running-bond wall has higher horizontal bending strength than a stack-bond wall, whereas the vertical bending strength of both walls is equal.
5. What measures are used to respond to the shrinkage of CMU walls?
6. Explain the differences between fine grout and coarse grout and where each is used.
7. Explain why granite is the most durable of all building stones. Where would you recommend the use of granite?
8. Explain the essential differences between marble and granite and their uses in buildings.
9. Explain what arching action in masonry is and its significance in building construction.

CHAPTER 26

Masonry and Concrete Bearing Wall Construction

CHAPTER OUTLINE

26.1 Traditional Masonry Bearing Wall Construction

26.2 Importance of Vertical Reinforcement in Masonry Walls

26.3 Bond Beams in a Masonry Bearing Wsc all Building

26.4 Wall Layout in a Bearing Wall Building

26.5 Floor and Roof Decks—Connections to Walls

26.6 Limitations of Masonry Bearing Wall Construction

26.7 Bearing Wall and Column-Beam System

26.8 Reinforced-Concrete Bearing Wall Construction

26.9 Reinforced-Concrete Tilt-Up Wall Construction

26.10 Connections in a Tilt-Up Wall Building

26.11 Exterior Cladding and Insulation in a Tilt-Up Wall Building

The use of masonry in contemporary buildings is primarily in the walls. Minor uses occur in interior flooring or exterior paving. Although masonry roofs (vaults, domes, and shells) were frequently constructed in the past, they are relatively uncommon in modern buildings.

Masonry walls may either be load-bearing or non-load-bearing walls. Non-load-bearing masonry walls include retaining walls, exterior infill and cladding, and interior partitions, Figure 26.1. Masonry cladding functions as an exterior weather-resistant cover and is similar to the exterior siding in a wood light-frame building. Masonry cladding is discussed in Chapter 28.

Masonry infill occupies the space between the concrete or steel-frame members. It may be used to resist the racking of the frame—that is, to serve as a shear wall. In that case, the infill must completely fill the space between the columns of the frame so that the lateral load is transferred from the columns to the infill and vice versa, Figure 26.2(a).

If the infill is not used as a shear wall, adequate separation between the columns and the infill is required so that the lateral load is not transferred from the columns to the infill, Figure 26.2(b).

Advantages of a Masonry Bearing Wall Building

A load-bearing wall (by definition) is a wall that supports gravity loads in addition to its self-load. Load-bearing walls may also act as shear walls. (However, as shown in Figure 26.1, some shear walls may be non-load-bearing walls, i.e., they may not support any gravity load other than their self-loads.)

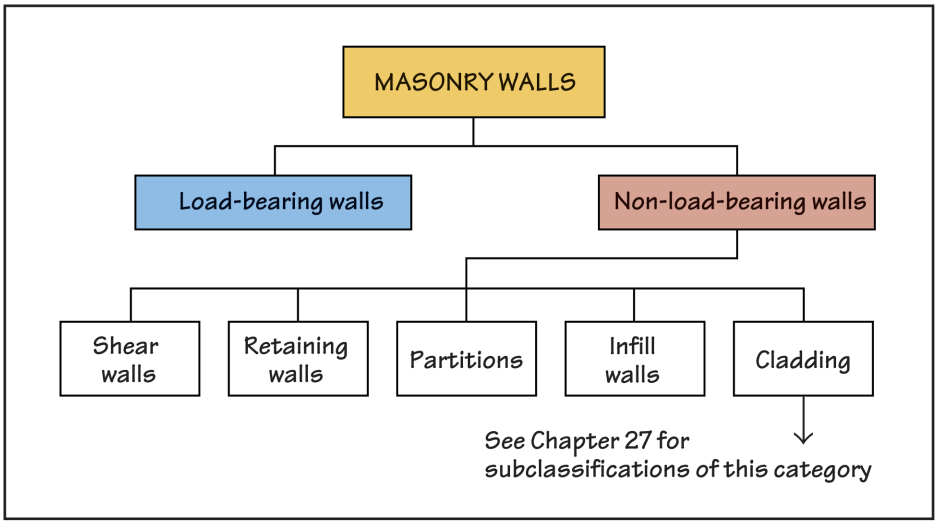
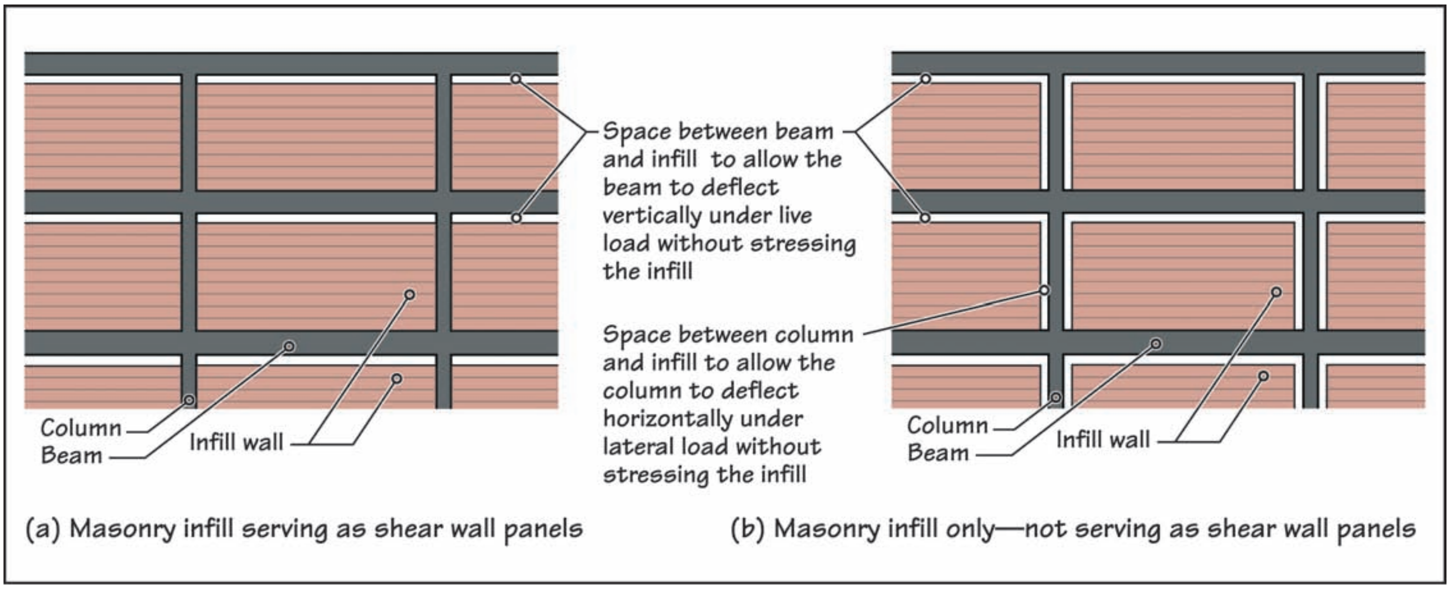

MASONRY WALLS
Load-bearing walls
Non-load-bearing walls
Shear walls
Retaining walls
Partitions
Infill walls
Cladding
See Chapter 27 for subclassifications of this category

FIGURE 26.1 Various applications of masonry walls.


Space between beam and infill to allow the beam to deflect vertically under live load without stressing the infill
Space between column and infill to allow the column to deflect horizontally under lateral load without stressing the infill
Column
Beam
Infill wall
Column
Beam
Infill wall

(a) Masonry infill serving as shear wall panels

(b) Masonry infill only—not serving as shear wall panels

FIGURE 26.2 Masonry infill between the members of a structural frame may or may not be used to resist shear (racking of the frame).

A major advantage of a load-bearing masonry structure, also called a *masonry bearing wall structure*, is that the walls that are required for load-bearing purposes may also function as shear walls in addition to enclosing and dividing spaces. This contrasts with a steel or concrete frame structure, where the frame serves the structural function only. Space-enclosing and dividing functions must, therefore, be performed by nonstructural walls. The separation of the structural and nonstructural elements in a frame structure requires careful detailing of the connections between them. Such details are unnecessary in a load-bearing masonry structure.

Constructed of an inherently fire-resistive, mold-free, sound-insulating, relatively inexpensive, and durable material, load-bearing masonry has a favorable life-cycle cost index. That is why masonry experts claim that load-bearing masonry is a more sustainable alternative to a concrete or steel-frame structure in many applications.

BEARING WALL STRUCTURES IN REINFORCED MASONRY AND REINFORCED CONCRETE

Although masonry has been used historically without any steel reinforcement, in contemporary times the use of plain (unreinforced) masonry is less common. Reinforced masonry has several advantages over plain masonry at little additional cost. As discussed in Section 26.2, reinforcement increases a masonry wall's flexural and shear strengths. Additionally, because steel is a ductile material, a reinforced-masonry wall is better able to absorb structural deformations by the yielding of steel—an important requirement for structures located in seismic regions. Plain masonry's ability to absorb deformations is limited due to the brittle nature of masonry.

Poor performance of unreinforced-masonry structures has been demonstrated again and again through studies of postearthquake and posthurricane building damage all over the world. However, it must be added that low-rise, plain-masonry bearing wall structures have excellent performance records in locations that are not subjected to earthquakes or extreme winds.

This chapter begins with an introduction to traditional load-bearing masonry, followed by a discussion of its contemporary alternative. Because there is a great deal of similarity between bearing wall construction in reinforced masonry and reinforced concrete, reinforced-concrete bearing wall construction is also covered in this chapter.

Reinforced-concrete bearing wall structures can be constructed of site-cast concrete or precast concrete. The precast-concrete bearing wall system is typically a concrete tilt-up wall system, which is also discussed in this chapter.

26.1 TRADITIONAL MASONRY BEARING WALL CONSTRUCTION

The masonry bearing wall system is one of the oldest construction systems. Until the invention of the frame structure, the masonry bearing wall system was the only system available for constructing major buildings. Although several large and tall masonry structures were built, their design was based on arbitrary rules formulated on an intuitive rather than a scientific basis. Gothic cathedrals symbolize the daring extremes to which such intuitive understanding was extended.

Over time, this intuitive understanding was embedded in the building codes as empirical rules for the design of masonry bearing walls. These rules required the thickness of exterior masonry walls to increase progressively toward the lower floors. The increase in wall thickness was necessary to accommodate greater gravity loads at the lower floors.

Another important reason for progressively increasing wall thickness at the base was to ensure stability against overturning by wind loads. (Very little was known at the time about seismic loads.) The code-required thickness was based on the assumption that all wind loads on the building were resisted by exterior walls only. In providing this resistance, each exterior wall functioned as a freestanding wall, behaving as a vertical cantilever fixed in the ground—like a flagpole, Figure 26.3.

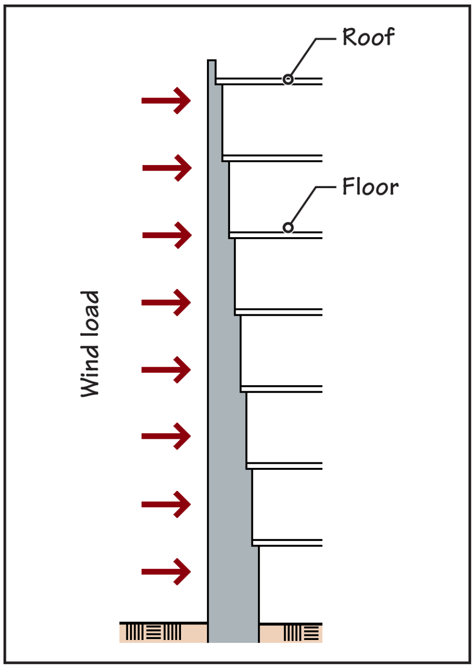


FIGURE 26.3 In resisting wind loads, the exterior walls in historic load-bearing masonry buildings were designed as freestanding cantilevers. Therefore, the thickness of walls at lower floors increased substantially with an increase in the height of the building.

This assumption made building code requirement highly conservative, necessitating extremely thick walls at the base of a tall building. That is why the exterior brick walls of the 215-ft-high, 16-story Monadnock Building (completed in 1891 in Chicago) are approximately 6 ft thick at the ground level.

Because the lower floors of a building are the most usable and profitable, it was apparent that high-rise masonry structures were economically unviable because of the unduly large percentage of floor area occupied by the walls. In fact, the Monadnock Building was the last high-rise masonry bearing wall structure in North America until the mid-twentieth century, when the system was revived using a more efficient structural design methodology.

In general, the interior structure of most historical masonry bearing wall buildings consisted of columns and beams. The columns were of cast iron and the beams were of wrought iron. In later structures, steel was substituted for both cast iron and wrought iron. In several masonry buildings, (heavy) timber columns and beams were used in the interior structure (Figure 1, Expand Your Knowledge, Chapter 15).

BEARING WALL SYSTEM—ITS ABANDONMENT AND REVIVAL

The use of the masonry bearing wall system for high-rise buildings went out of favor as the skeleton (iron and, later, steel) frame became popular. Steel is much stronger than masonry. Therefore, the columns in a frame structure were much smaller than those in masonry bearing walls. Because the walls in a frame structure are nonstructural, their thickness was considerably reduced. This conserved valuable floor space. A secondary advantage of the skeleton frame was the speed with which it could be erected compared to thick masonry walls.

The beginning of the twentieth century saw major advances in the science of structural engineering, particularly in the area of design and analysis of frames and continuous beams. Advances were also made in the science of materials related to steel and reinforced concrete. Because masonry does not lend itself to frame construction, it was largely displaced from the realm of structural materials.

CONTEMPORARY BEARING WALL CONSTRUCTION

The situation began to change with reconstruction work in Europe after World War II, which required the construction of large-scale and relatively inexpensive housing. This was also the time when the structural design theories of reinforced concrete became fairly sophisticated. The extension of these theories to masonry, which, as a material, is not vastly different from concrete, was logical. Additionally, architects and engineers began to understand the interactive structural behavior of the walls and horizontal components (floors and roof) of a building.

During the 1950s, several high-rise masonry bearing wall buildings were built, initially in Europe and subsequently in North America. The design was based on a rational engineering approach rather than on the earlier empirical rules.

The structural behavior of a contemporary masonry bearing wall building is similar to that of conventional wood light-frame construction (see Principles in Practice in Chapter 15). However, the construction details required to respond to the structural behavior are not identical. The reason is that in a masonry bearing wall building, the walls, floors, and roof are solid components, whereas in a wood light-frame building, they consist of linear frame members with intervening cavity spaces.

26.2 IMPORTANCE OF VERTICAL REINFORCEMENT IN MASONRY WALLS

Using the contemporary rational design approach, it is possible to design masonry bearing wall residential structures (apartment buildings, hotels, and motels) of approximately 20 stories using 8- to 10-in.-thick walls. In fact, an 8-in.-thick CMU wall is the industry's standard for masonry bearing wall structures. For long-span buildings with relatively high walls, such as those used in gymnasiums, warehouses, and large assembly spaces, 10- or 12-in.-thick CMU walls may be needed. CMU walls thicker than 12 in. are rare.

For a one- or two-story building in a low-wind or nonseismic region, it may be possible to design masonry walls without any vertical reinforcement in some situations. In a taller building or a building in a high-wind or seismic region, vertical reinforcement is generally always needed. (Masonry walls without vertical reinforcement are referred to as *plain-masonry* walls, and those with vertical reinforcement are called *reinforced-masonry* walls.)

The benefits of reinforced masonry over plain masonry are as follows:

- Reinforcement increases the strength of a wall against bending caused by (a) eccentric gravity loads on the wall and (b) lateral loads perpendicular to the wall, Figure 26.4.
- Reinforcement increases the sliding resistance of the wall to in-plane lateral loads (as in a shear wall), reducing horizontal displacement between floors, Figure 26.5. In other words, reinforcement stitches the floors together. Additionally, it provides positive anchorage between the wall and the foundation.
- Reinforcement helps to resist the tension caused by overturning of the wall, Figure 26.6 (and functions like hold-down bolts in a wood light-frame building, see Principles in Practice in Chapter 15). Therefore, both ends of a masonry wall are typically reinforced. Reinforcement is also provided near both ends of a door or window opening. Reinforcement at the ends of an opening also helps to absorb the impact from slamming of a door or window.

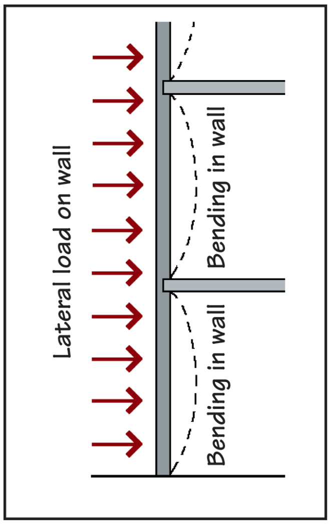


FIGURE 26.4 Bending in a wall caused by lateral loads or eccentric gravity loads on the wall. Vertical wall reinforcement increases the wall's bending strength.

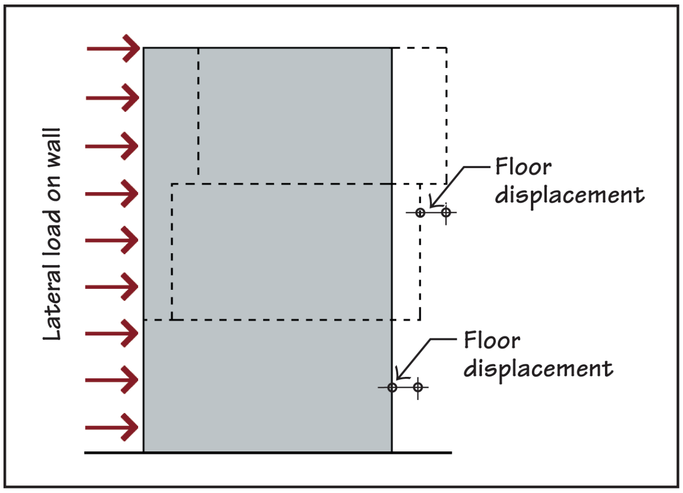


FIGURE 26.5 Vertical reinforcement helps stitch floors together, reducing the horizontal displacement between floors (story drift) caused by lateral loads on the building.

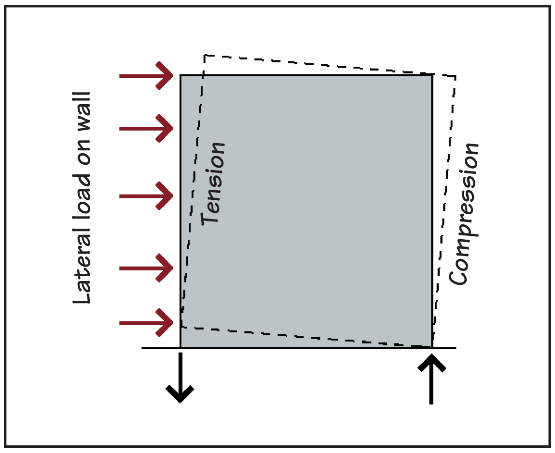


FIGURE 26.6 Vertical reinforcement helps resist tension caused by overturning of the wall by lateral loads. Because lateral loads can act on either side of a wall, both ends of a wall require reinforcing.

26.3 BOND BEAMS IN A MASONRY BEARING WALL BUILDING

In most masonry bearing wall structures, the floors consist of precast concrete hollow-core slabs, metal deck, or wood deck. Being individual elements, they do not have the continuity to resist diaphragm tension (see Principles in Practice in Chapter 15). Therefore, they are anchored to masonry beams called *bond beams*. Because a bond beam is reinforced and continuous, it is able to resist the diaphragm tension.

A bond beam is provided at each floor level and roof level in all exterior walls and at all interior bearing walls and shear walls, Figure 26.7. A bond beam is also provided at the top of the parapet. A parapet-level bond beam does not have a structural function but instead facilitates the anchorage of coping on the wall.

Floor- and roof-level bond beams are similar to the bond beams used for shrinkage crack control in CMU walls (see Figure 25.22). However, floor- and roof-level bond beams are generally more heavily reinforced than those used for crack control.

Generally, a bond beam is only one unit (8 in.) deep but, if needed, its depth can be increased to 16 in. by grouting the regular concrete masonry units below (or above) the bond beam units, Figure 26.8. The reinforcement in a bond beam must be continuous to be able to effectively absorb diaphragm tension. It must, therefore, be adequately lap spliced between the ends of bars, particularly at wall corners and intersections.

Because a bond beam is a grouted element, it provides a suitable base on which the roof or floor trusses and joists can be supported and anchored. Some architects and engineers prefer to use site-cast reinforced-concrete bond beams, Figure 26.9, which are more robust than masonry bond beams. However, because a site-cast concrete bond beam requires formwork, its construction is more cumbersome than that of a masonry bond beam.

VERTICAL REINFORCEMENT AND BOND BEAM COMBINATION—A REINFORCED-MASONRY FRAME

The combination of bond beams and vertically reinforced (and grouted) CMU cells forms a reinforced-masonry frame, Figure 26.10. The frame ties the intervening plain masonry into an integral mass, increasing the wall's resistance to lateral loads. The system is identical to a reinforced-concrete frame with plain-masonry infill that is a common form of construction in many countries.

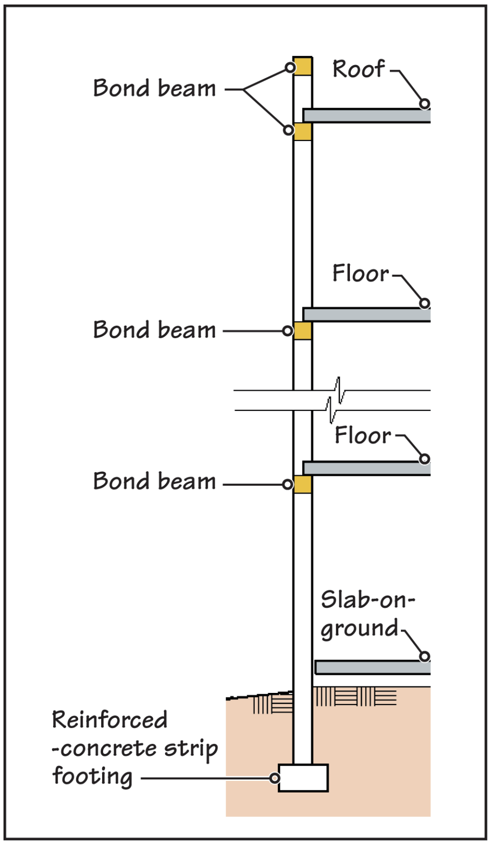

Bond beam
Roof
Floor
Bond beam
Floor
Bond beam
Slab-on-ground
Reinforced -concrete strip footing

FIGURE 26.7 Locations of bond beams in a masonry bearing wall structure.

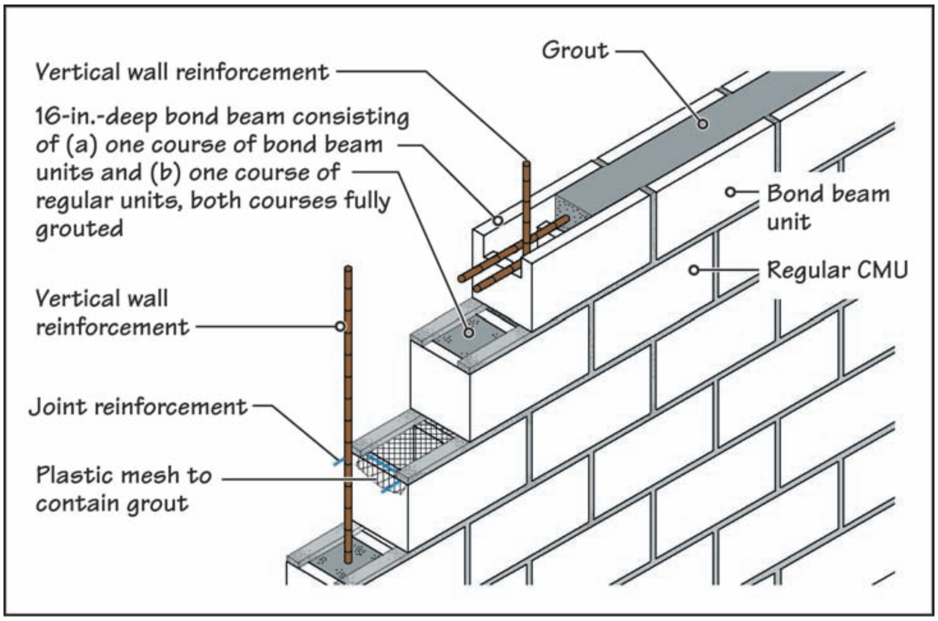

Vertical wall reinforcement
Grout
16-in.-deep bond beam consisting of (a) one course of bond beam units and (b) one course of regular units, both courses fully grouted
Bond beam unit
Regular CMU
Vertical wall reinforcement
Joint reinforcement
Plastic mesh to contain grout

FIGURE 26.8 Detail of a 16-in.-deep bond beam in a CMU wall (see also Chapter 25, Figure 25.22).

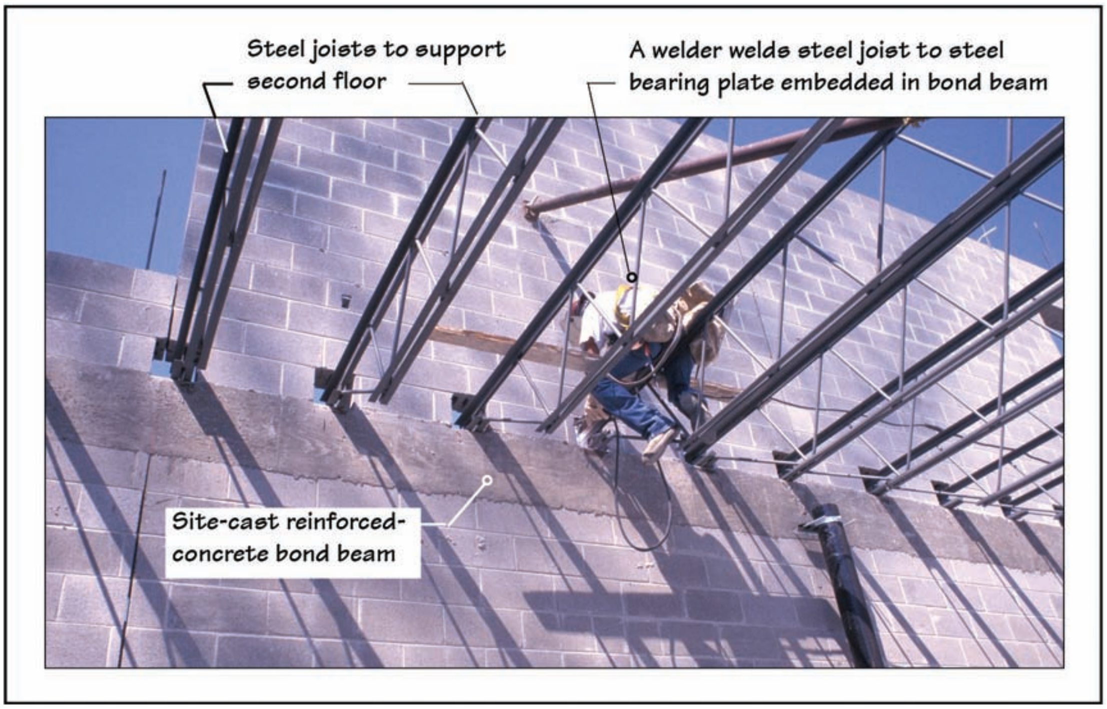

Steel joists to support second floor
A welder welds steel joist to steel bearing plate embedded in bond beam
Site-cast reinforced-concrete bond beam

FIGURE 26.9 A site-cast reinforced-concrete bond beam at the second floor level of a load-bearing masonry wall building.

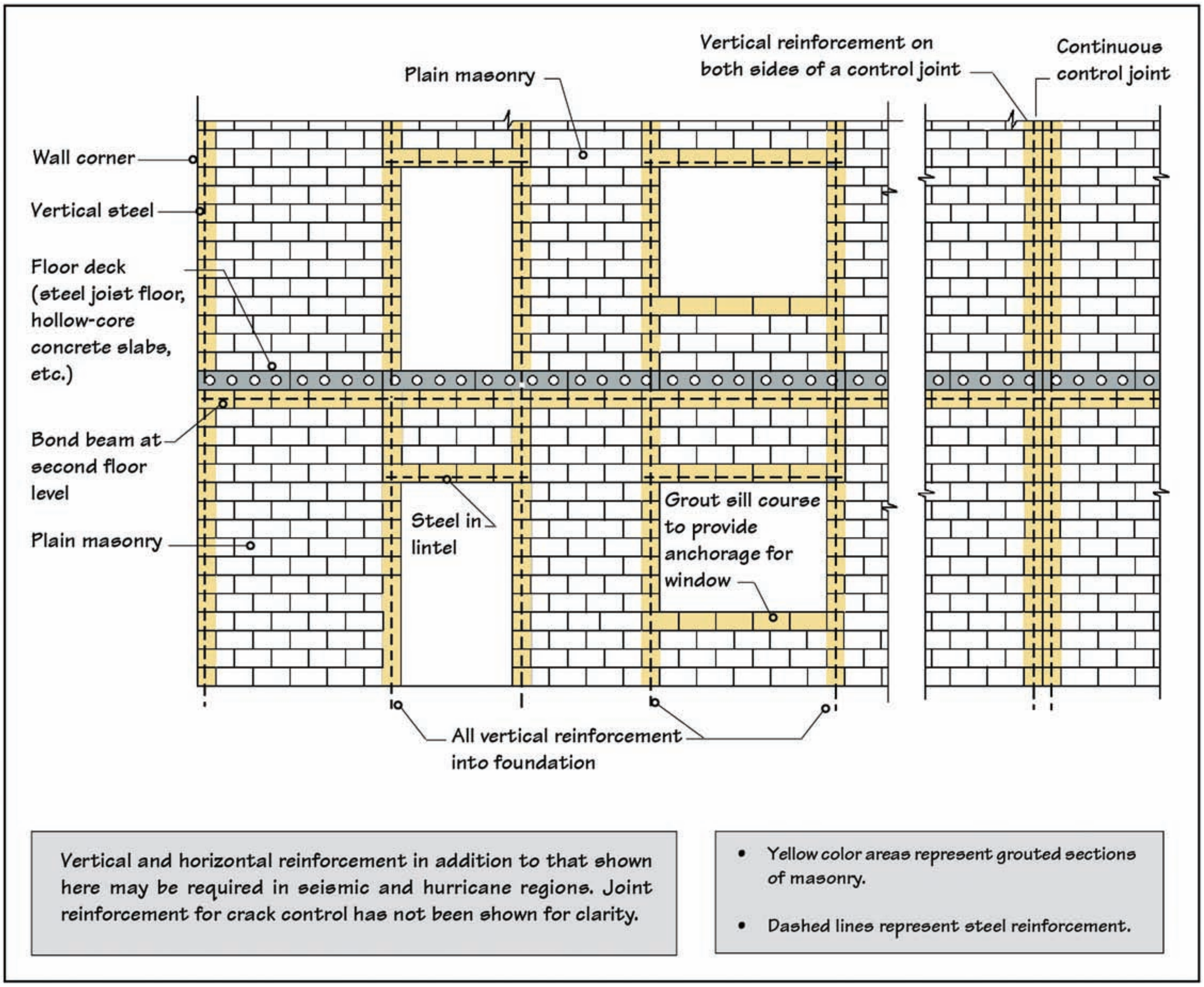

Plain masonry
Vertical reinforcement on both sides of a control joint
Continuous control joint
Wall corner
Vertical steel
Floor deck (steel joist floor, hollow-core concrete slabs, etc.)
Bond beam at second floor level
Plain masonry
Steel in lintel
Grout sill course to provide anchorage for window
All vertical reinforcement into foundation
Vertical and horizontal reinforcement in addition to that shown here may be required in seismic and hurricane regions. Joint reinforcement for crack control has not been shown for clarity.
Yellow color areas represent grouted sections of masonry.
Dashed lines represent steel reinforcement.

FIGURE 26.10 The combination of (reinforced) bond beams and vertically reinforced cells in a masonry wall (both yellow highlighted) is similar to a reinforced-concrete beam-and-column structural frame with intervening plain-masonry infill.

26.4 WALL LAYOUT IN A BEARING WALL BUILDING

For a bearing wall building to be structurally efficient, a sufficient number and adequate lengths of walls must be provided in both principal directions of a building, yielding a *cellular-type* plan. The simplest cellular-type plan is a single-story rectangular (box-type) structure, commonly used for long-span bearing wall buildings (gymnasiums, lecture halls, and other large assembly or storage spaces), Figure 26.11.

For a multifloor bearing wall structure, a cellular-type structure is best achieved when the walls at an upper floor are at the same location as the ones on a lower floor, resulting in repetitive floor plans, Figure 26.12. Repetitive floor plans are not only structurally more efficient but also more easily constructible. They allow greater prefabrication and familiarity with the construction process, giving economy.

A multifloor bearing wall structure is, therefore, ideal for occupancies in which economy is a major consideration, and a cellular-type, repetitive floor layout is intrinsic to the occupancy. Such occupancies are generally residential—apartment buildings, hotels, motels, student dormitories, correction facilities, hospital wards, and so on.

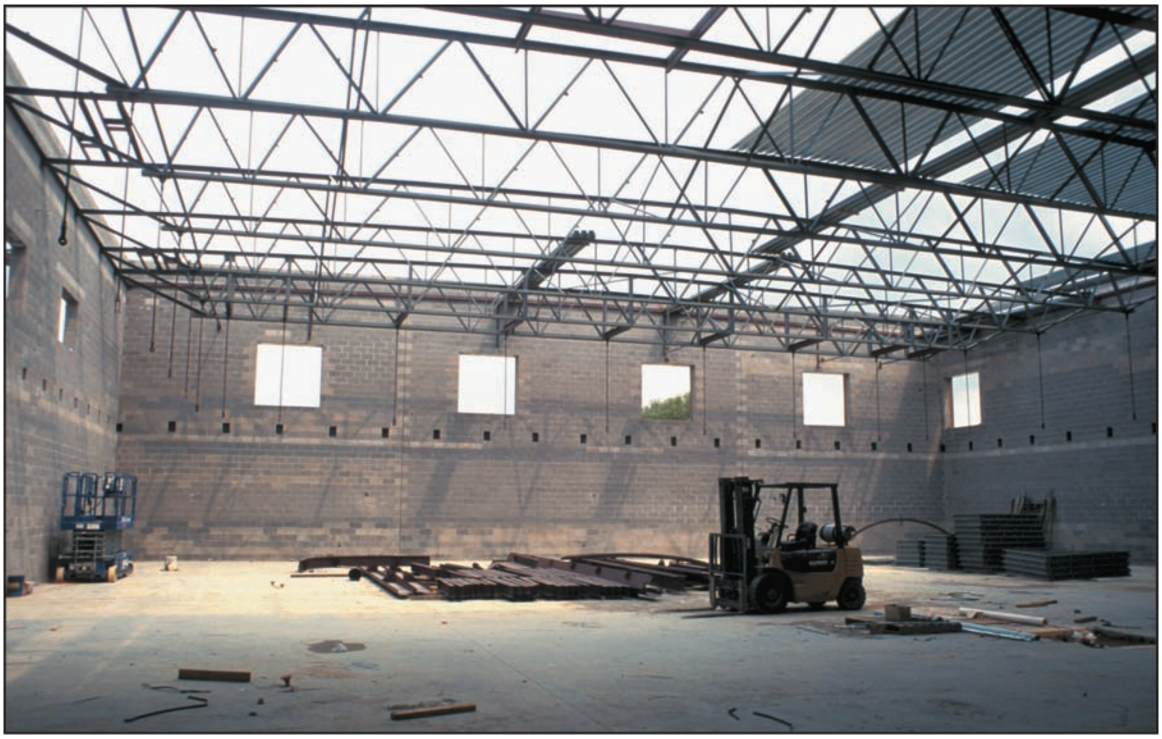


FIGURE 26.11(a) A gymnasium with 12-in.-thick CMU bearing walls (in a box-type floor plan) and a steel joist roof. The joists span nearly 100 ft between walls and are approximately 60 in. deep.

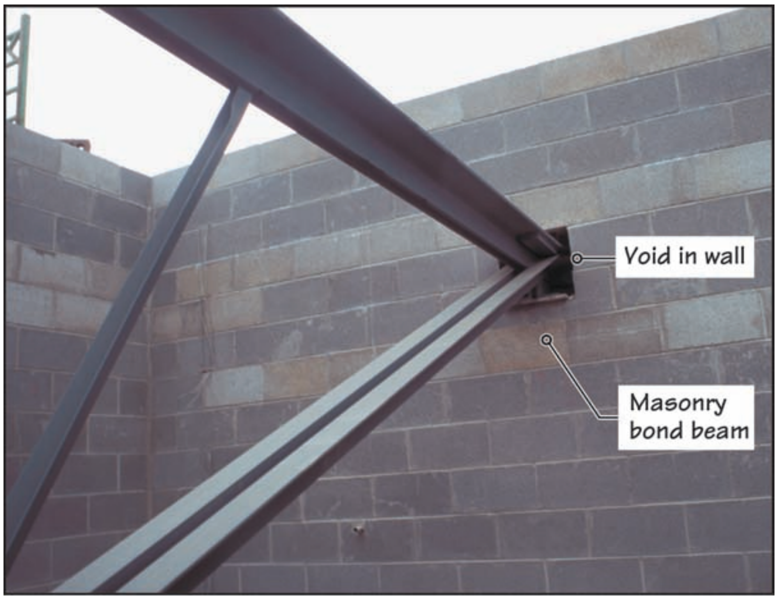


FIGURE 26.11(b) Support for joists of the building in Figure 26.11(a). Voids, which contain steel bearing plates, are left in the wall at support locations during the construction of the wall. A continuous masonry bond beam is provided under the voids.

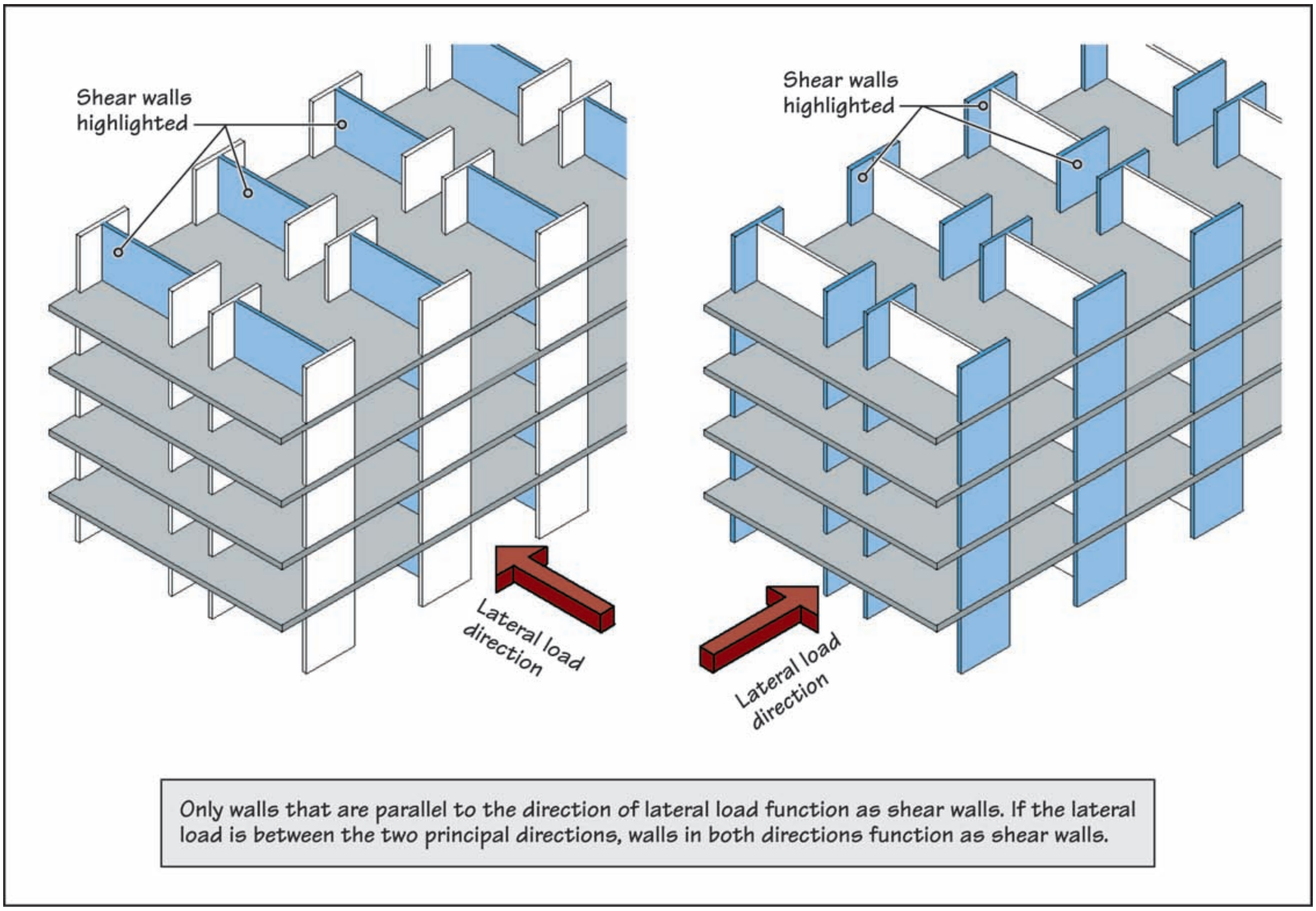

Shear walls highlighted
Lateral load direction
Shear walls highlighted
Lateral load direction
Only walls that are parallel to the direction of lateral load function as shear walls. If the lateral load is between the two principal directions, walls in both directions function as shear walls.

FIGURE 26.12 A bearing wall structure should have lateral load–resisting (shear) walls in both principal directions. Each figure shows the walls that function as shear walls when subjected to lateral load in one principal direction.

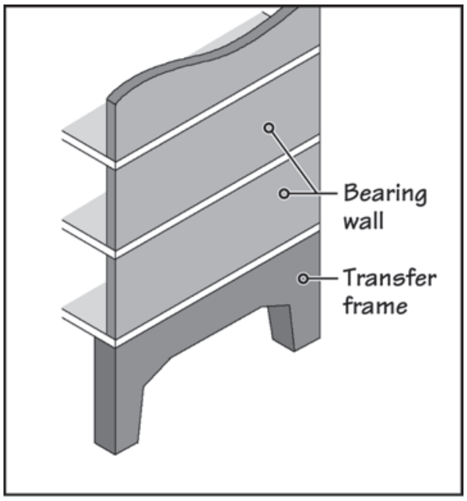

Bearing wall
Transfer frame

FIGURE 26.13 Transfer frame at the first floor or basement level of a multistory bearing wall structure. The frame must have adequate stiffness to preclude the existence of a soft story.

Repetitiveness of floor layout requires that all load-bearing or shear walls are continuous to the foundation. This is particularly important in high-rise bearing wall structures, where there is a temptation to provide larger uninterrupted spaces at the first-floor or basement level.

The discontinuity of walls at foundations, referred to as a *soft story*, is structurally feasible but requires a heavy transfer structure, Figure 26.13. The transfer structure carries the superimposed gravity loads and provides the required lateral load resistance. A soft story is particularly problematic in seismic zones.

Another desirable attribute of a bearing wall structure is symmetry in wall layout. An asymmetrical wall layout leads to rotation of the building (torsion) under lateral loads. The greater the asymmetry, the greater the torsion created, which increases the cost of the structure.

ROLE OF FLOOR AND ROOF DECKS IN THE WALL LAYOUT

Floor and roof slabs can either be one-way or two-way slabs (see Chapter 23). In a one-way slab, the slab spans between two opposite walls; that is, the gravity load on the slab is carried in one direction across the two opposite walls. In a two-way slab, the load is transferred to all four walls. Two-way slabs generally of site-cast concrete.

One-way slabs, which are more commonly used, may be of steel, precast concrete, or wood. The use of one-way slabs yields the following two types of bearing wall plans:

- Cross-bearing wall plan
- Longitudinal-bearing wall plan

In a cross-bearing wall plan, the bearing walls are transverse to the main axis of the building. Figure 26.14 compares the suitability of a few cross-bearing wall plans. A similar analysis for longitudinal-bearing wall plans is presented in Figure 26.15. Larger openings are generally possible with a cross-bearing wall plan. It is, therefore, more commonly used. A longitudinal-bearing wall plan provides larger, unobstructed interior spaces. It is used where interior walls are architecturally undesirable.

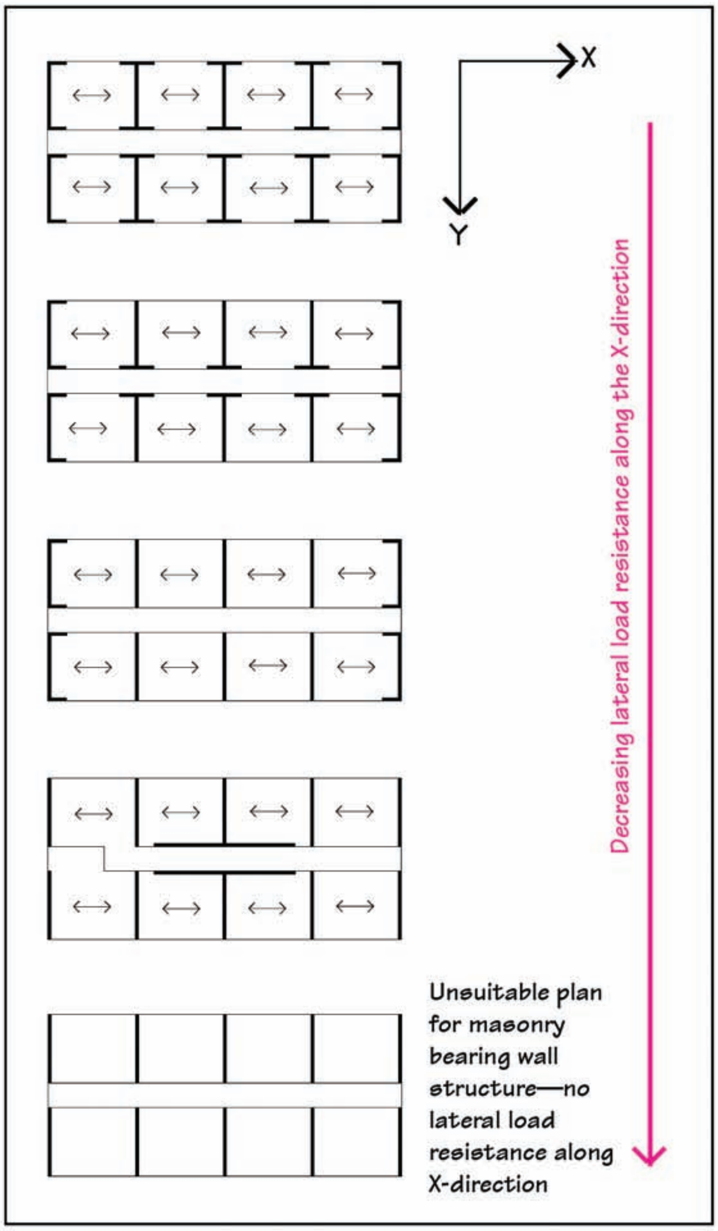

X
Y
Decreasing lateral load resistance along the X-direction
Unsuitable plan for masonry bearing wall structure—no lateral load resistance along X-direction

FIGURE 26.14 Relative suitability of various cross-bearing wall plans [Ref. 26.1].

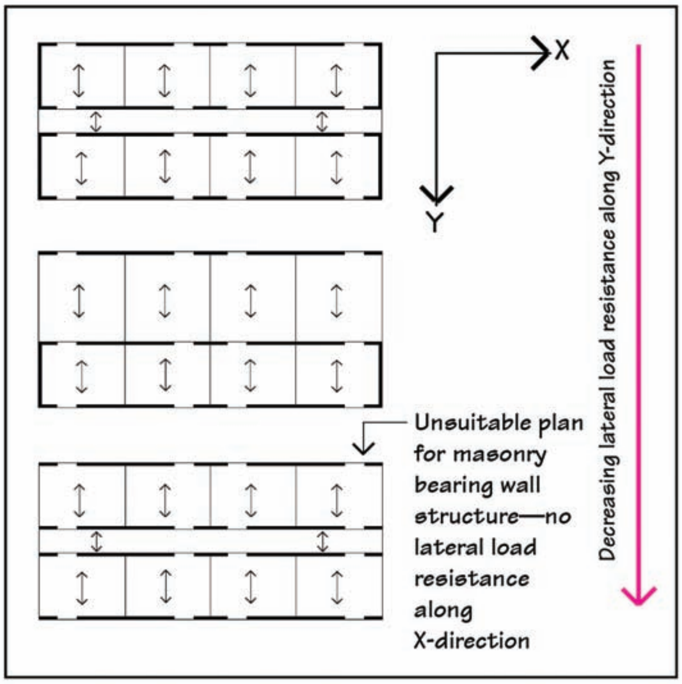

X
Y
Decreasing lateral load resistance along Y-direction
Unsuitable plan for masonry bearing wall structure—no lateral load resistance along X-direction

FIGURE 26.15 Relative suitability of various longitudinal-bearing wall layouts [Ref. 26.1]. Note that a longitudinal-bearing wall plan provides larger, unobstructed interior spaces compared with a cross-bearing wall plan.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. Historical load-bearing masonry structures were designed with the assumption that
   - **a.** all wind loads on the building were resisted by exterior walls only, and in doing so, they interacted with each other structurally.
   - **b.** all wind loads on the building were resisted by exterior walls only, with no structural interaction between them.
   - **c.** both interior and exterior walls resisted wind loads.
   - **d.** interior and exterior walls and floor and roof diaphragms resisted wind loads collectively.
   - **e.** none of the above.
2. Use of the load-bearing masonry wall system became extinct for a while and was revived
   - **a.** around the early nineteenth century.
   - **b.** around the mid-nineteenth century.
   - **c.** around the late nineteenth century.
   - **d.** after World War I.
   - **e.** after World War II.
3. The structural behavior of a contemporary load-bearing masonry wall building is similar to that of a
   - **a.** conventional wood light-frame building.
   - **b.** site-cast reinforced-concrete frame building.
   - **c.** precast-concrete frame building.
   - **d.** steel-frame building.
   - **e.** none of the above.
4. Referring to a masonry wall as a *reinforced-masonry wall* implies that the wall contains
   - **a.** horizontal reinforcing bars.
   - **b.** joint reinforcement.
   - **c.** vertical reinforcing bars.
   - **d.** bond beams.
   - **e.** none of the above.
5. Masonry walls without joint reinforcement are called *plain-masonry walls*.
   - **a.** True
   - **b.** False
6. A bond beam in a masonry bearing wall building is required for structural reasons
   - **a.** above all openings in exterior walls.
   - **b.** at each floor level.
   - **c.** at each floor level and roof level.
   - **d.** at each floor level, roof level, and top of the parapet.
   - **e.** none of the above.

(*Continued*)

7. A bond beam in a masonry bearing wall building must be a
- **a.** steel, reinforced-concrete, reinforced-masonry, or wood beam.
- **b.** steel, reinforced-concrete, or reinforced-masonry beam.
- **c.** steel or reinforced-concrete beam.
- **d.** reinforced-concrete or reinforced-masonry beam.
- **e.** none of the above.

8. A bond beam in a masonry bearing wall building
- **a.** is preferably used along the shorter span.
- **b.** is preferably used along the longer span.
- **c.** may be used along the shorter or longer span.
- **d.** is embedded in the walls.
- **e.** none of the above.

9. A typical bond beam is provided with
- **a.** horizontal reinforcement.
- **b.** stirrups.
- **c.** horizontal reinforcement and stirrups.
- **d.** none of the above.

10. A load-bearing wall structure works best when the floor plan of the building has
- **a.** walls that are distributed almost uniformly in both principal directions.
- **b.** walls at an upper floor that align with the walls at a lower floor.
- **c.** walls that are continuous up from the foundations.
- **d.** all of the above.

11. A cellular-type floor plan in a multistory building is generally inherent in the following occupancies:
- **a.** Residential occupancies
- **b.** Business occupancies
- **c.** Educational occupancies
- **d.** Mercantile occupancies
- **e.** None of the above

12. In a cross-bearing wall structure, the load-bearing walls are
- **a.** perpendicular to the main axis of the building.
- **b.** parallel to the main axis of the building.
- **c.** (a) or (b).
- **d.** (a) and (b).

13. Compared to a longitudinal-bearing wall floor plan, a cross-bearing wall floor plan generally gives larger exterior wall openings.
- **a.** True
- **b.** False

26.5 FLOOR AND ROOF DECKS—CONNECTIONS TO WALLS

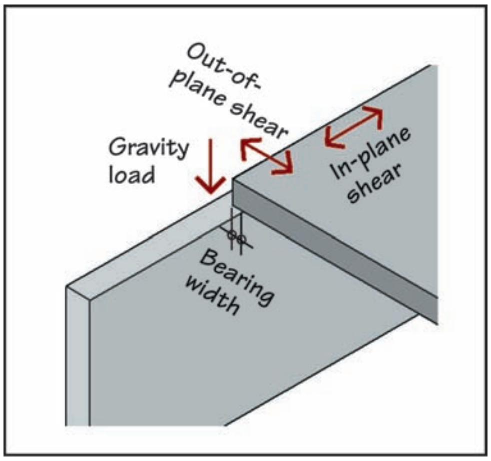


FIGURE 26.16 Connection forces between a floor (or roof) deck and a bearing wall.

The structural integrity of a bearing wall building depends on the connections between the walls and the floor or roof decks. As shown in Figure 26.16, a connection between a floor or roof and a wall must be adequate to sustain the following three forces:

- Gravity load from the floor or roof deck to the wall
- Out-of-plane shear between the wall and the floor or roof deck
- In-plane shear between the wall and the floor or roof deck

Figures 26.17 to 26.21 show typical connection details between masonry walls and various commonly used floor and roof decks—precast concrete, steel deck, and wood. Precast-concrete hollow-core slabs are most commonly used in mid- to high-rise masonry bearing wall residential buildings. As stated in Chapter 23, precast

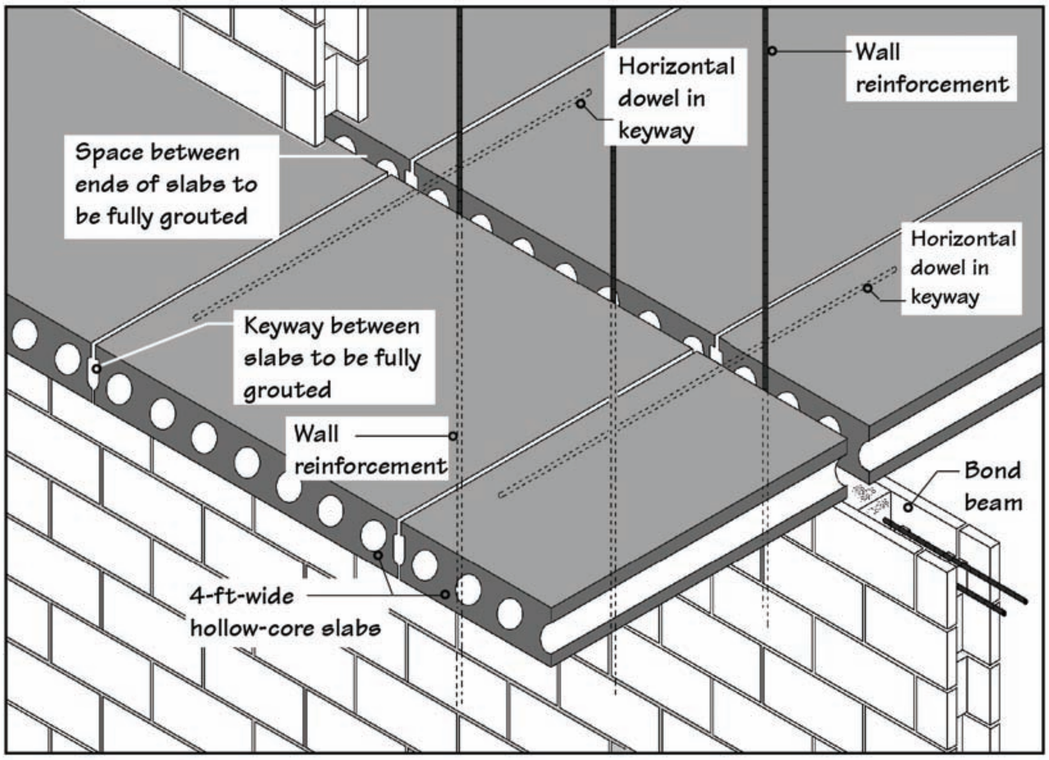

Horizontal dowel in keyway
Wall reinforcement
Space between ends of slabs to be fully grouted
Horizontal dowel in keyway
Keyway between slabs to be fully grouted
Wall reinforcement
Bond beam
4-ft-wide hollow-core slabs

FIGURE 26.17 Schematic connection detail between an interior concrete masonry bearing wall and 4-ft-wide hollow-core precast concrete slabs. Detail is similar if the hollow-core slabs are 8 ft wide; see Figure 26.23(c).

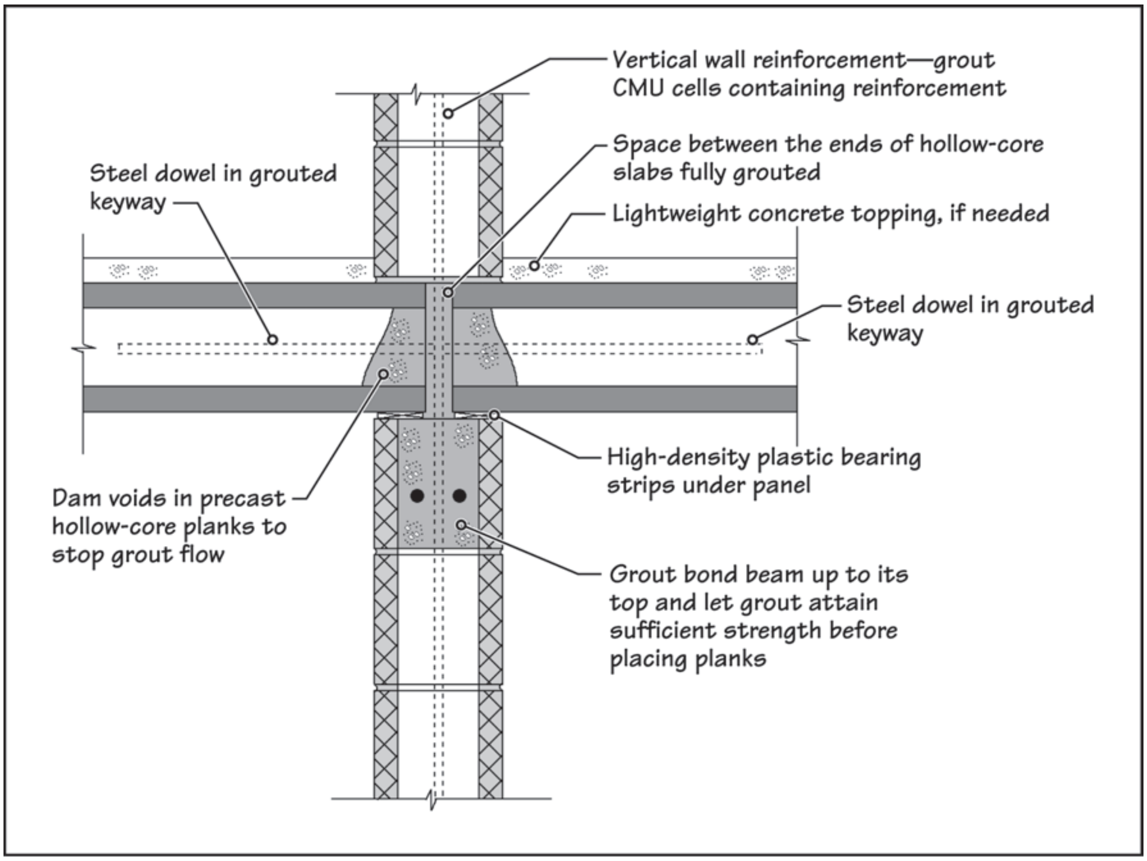

Vertical wall reinforcement—grout CMU cells containing reinforcement
Space between the ends of hollow-core slabs fully grouted
Steel dowel in grouted keyway
Lightweight concrete topping, if needed
Steel dowel in grouted keyway
High-density plastic bearing strips under panel
Dam voids in precast hollow-core planks to stop grout flow
Grout bond beam up to its top and let grout attain sufficient strength before placing planks

FIGURE 26.18 Detail of Figure 26.17 shown in section.

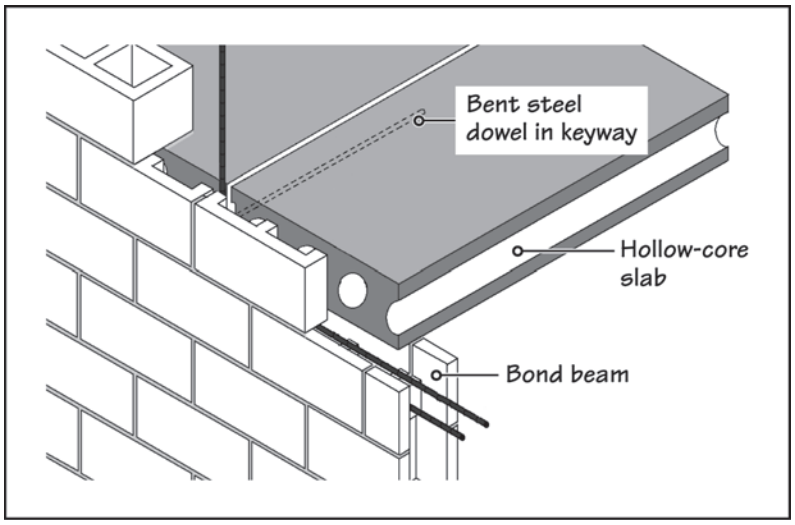

Bent steel dowel in keyway
Hollow-core slab
Bond beam

FIGURE 26.19 Schematic connection detail between an exterior concrete masonry bearing wall and hollow-core precast concrete slabs.

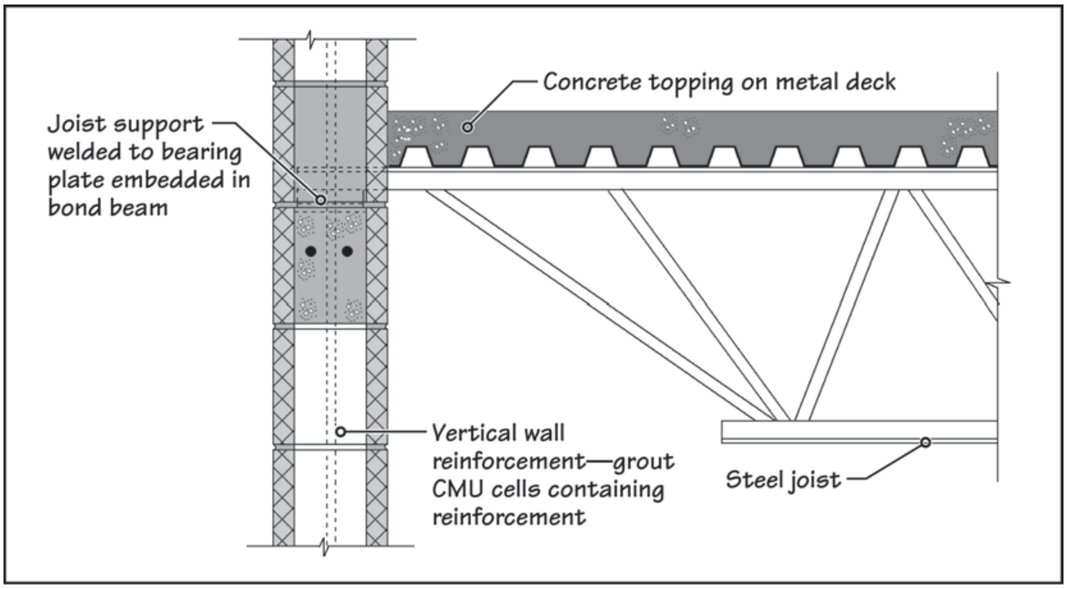

Concrete topping on metal deck
Joist support welded to bearing plate embedded in bond beam
Vertical wall reinforcement—grout CMU cells containing reinforcement
Steel joist

FIGURE 26.20 A schematic connection detail between a load-bearing masonry wall and a steel joist with a metal deck floor.

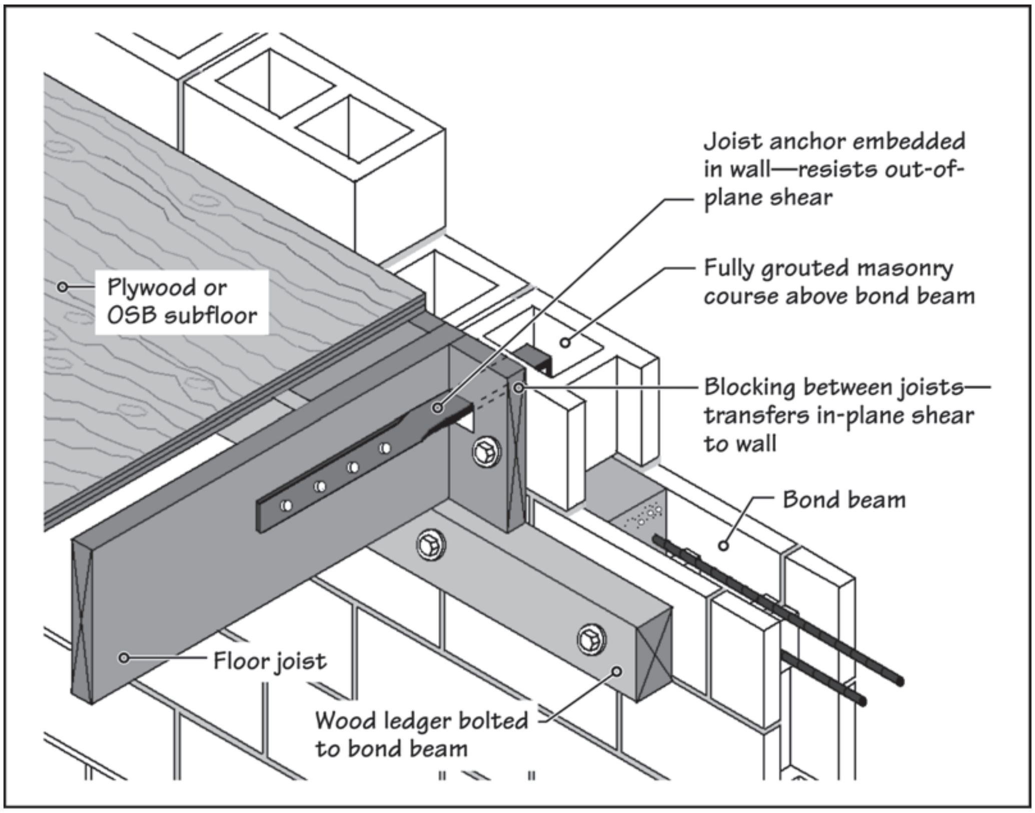

Joist anchor embedded in wall—resists out-of-plane shear
Fully grouted masonry course above bond beam
Plywood or OSB subfloor
Blocking between joists—transfers in-plane shear to wall
Bond beam
Floor joist
Wood ledger bolted to bond beam

FIGURE 26.21 A schematic connection detail between a load-bearing masonry wall and a wood light-frame floor.

hollow-core slabs are produced in various widths (widths of 4 ft and 8 ft are more common). Steel and wood decks are common in low-rise buildings.

26.6 LIMITATIONS OF MASONRY BEARING WALL CONSTRUCTION

As stated in Section 25.1, cutting masonry units increases the cost of construction and also slows it down, so it is generally avoided in masonry structures. Consequently, the length of a masonry wall is based on modular dimensions. In CMU walls, the module is 8 in. Therefore, the lengths of CMU walls and opening widths are multiples of 8 in.

With a mortar joint thickness of $\frac{3}{8}$ in., the clear size of an opening is $\frac{3}{8}$ in. greater than that given by the multiple of 8 in. In other words, the rough opening width is 3 ft 4$\frac{3}{8}$ in. (40$\frac{3}{8}$ in.), not 3 ft 4 in. (40 in.), Figure 26.22(a).

Similarly, the width of the masonry wall between openings is $\frac{3}{8}$ in. less than that given by the multiples of 8 in. Thus, the length of masonry between openings is 1 ft 3$\frac{5}{8}$ in. (15$\frac{5}{8}$ in.), not 1 ft 4 in. (16 in.).

NOTE

The dimension of a masonry opening is $\frac{3}{8}$ in. greater than the multiples of a masonry unit module. The dimension of the masonry between openings is $\frac{3}{8}$ in. less than the multiples of the masonry unit module.

The 8-in. module also applies to height dimensions. Thus, the floor-to-ceiling heights in a CMU masonry wall building are generally 8 ft, 8 ft 8 in., 9 ft 4 in., and so on. Similarly, a rough door-opening height of 7 ft 4$\frac{3}{8}$ in., shown in Figure 26.22(b), is commonly used. This dimension is (slightly) excessive for a standard 7-ft-0-in.-high door.

Where standard-height doors are desired, a starter course of saw-cut masonry units may be used. (However, note that in most commercial construction, doors and windows are custom fabricated to opening dimensions. Therefore, standard door and window dimensions generally do not apply to commercial construction.)

WATER-RESISTIVE EXTERIOR FINISH REQUIRED

Because contemporary masonry bearing walls are relatively thin, they require some form of weather-resistive exterior coating (clear coating or paint), plaster (stucco or EIFS), or some form of cladding to prevent water from entering the interior (see Chapters 28 and 29 for a discussion of exterior cladding). Exterior walls in traditional masonry structures did not require such cladding because their thickness made them inherently water resistive.

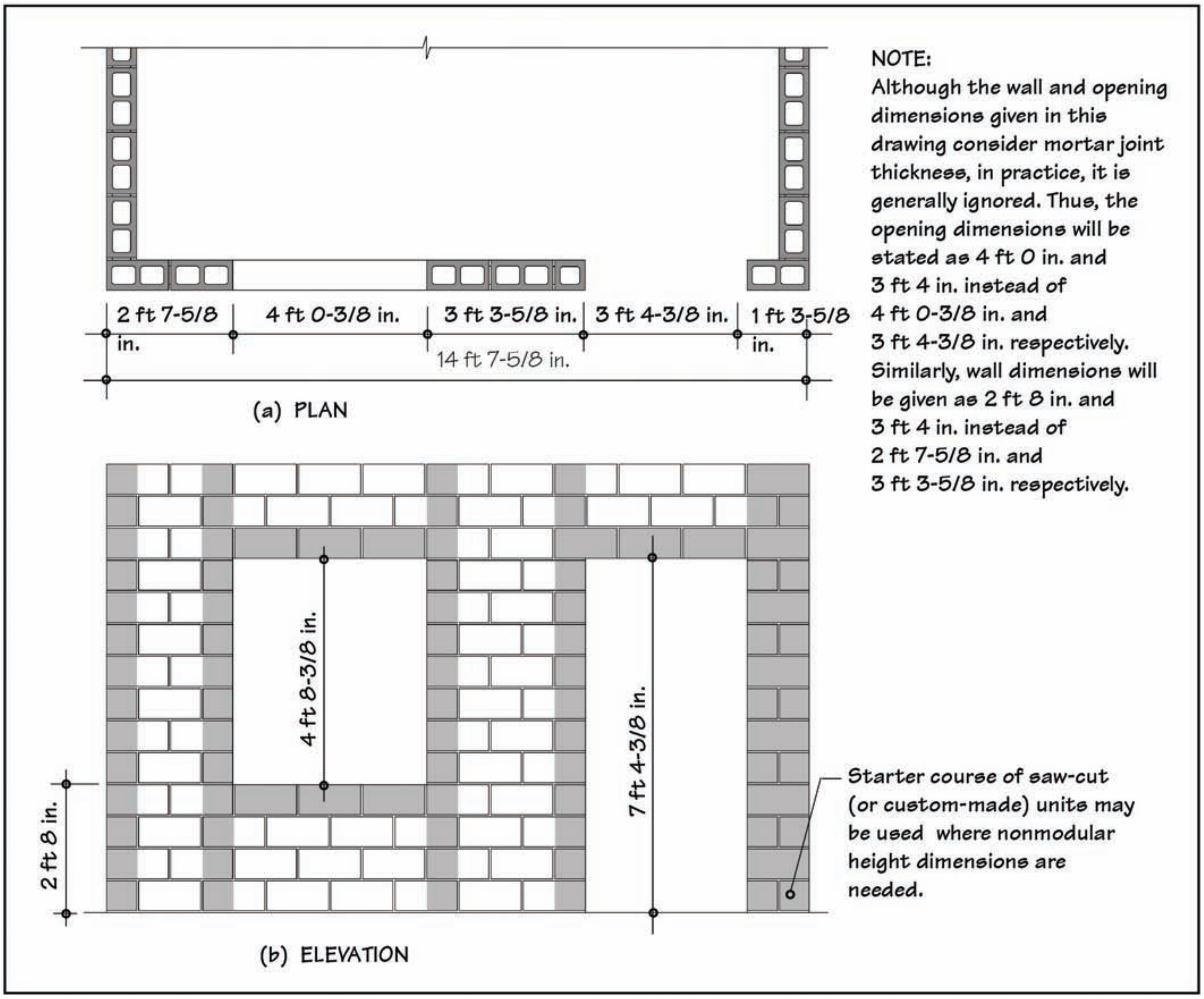

NOTE:
Although the wall and opening dimensions given in this drawing consider mortar joint thickness, in practice, it is generally ignored. Thus, the opening dimensions will be stated as 4 ft 0 in. and 3 ft 4 in. instead of 4 ft 0-3/8 in. and 3 ft 4-3/8 in. respectively. Similarly, wall dimensions will be given as 2 ft 8 in. and 3 ft 4 in. instead of 2 ft 7-5/8 in. and 3 ft 3-5/8 in. respectively.
2 ft 7-5/8 in.
4 ft 0-3/8 in.
3 ft 3-5/8 in.
3 ft 4-3/8 in.
1 ft 3-5/8 in.
14 ft 7-5/8 in.
(a) PLAN
4 ft 8-3/8 in.
7 ft 4-3/8 in.
2 ft 8 in.
Starter course of saw-cut (or custom-made) units may be used where nonmodular height dimensions are needed.
(b) ELEVATION

FIGURE 26.22 Effect of modularity of CMUs on the dimensions of walls and openings.

COORDINATION BETWEEN TRADES DURING CONSTRUCTION

Electrical conduit and junction boxes and other utility lines need to be built into walls as the construction progresses. Door frames are generally erected in position, and the walls are built around them. Therefore, greater coordination between various trades is needed during the construction of a masonry building than is required for a steel- or concrete-frame building. Where precast-concrete floor slabs are used, detailed shop drawings are required to indicate the location of openings for vertical continuity of service lines.

Figures 26.23(a) to (e) illustrate the highlights of the construction process of a typical high-rise masonry bearing wall building, and Figure 26.23(f) shows the finished building.

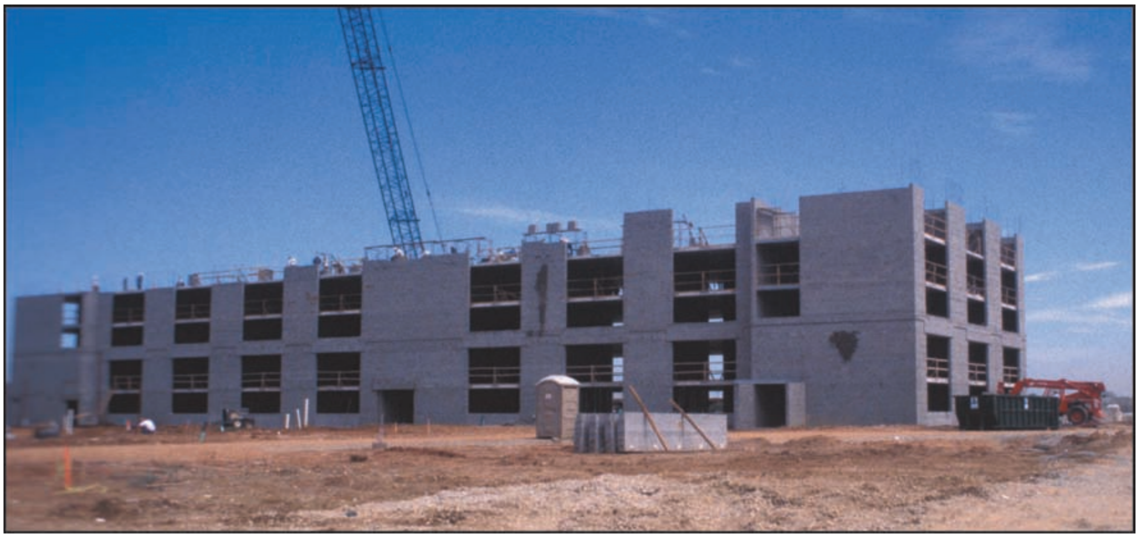


FIGURE 26.23(a) This and the following five images show the construction of an eight-story load-bearing masonry hotel building. The building, with a cross-bearing wall plan (see Figure 26.14), is in its early stages of construction.

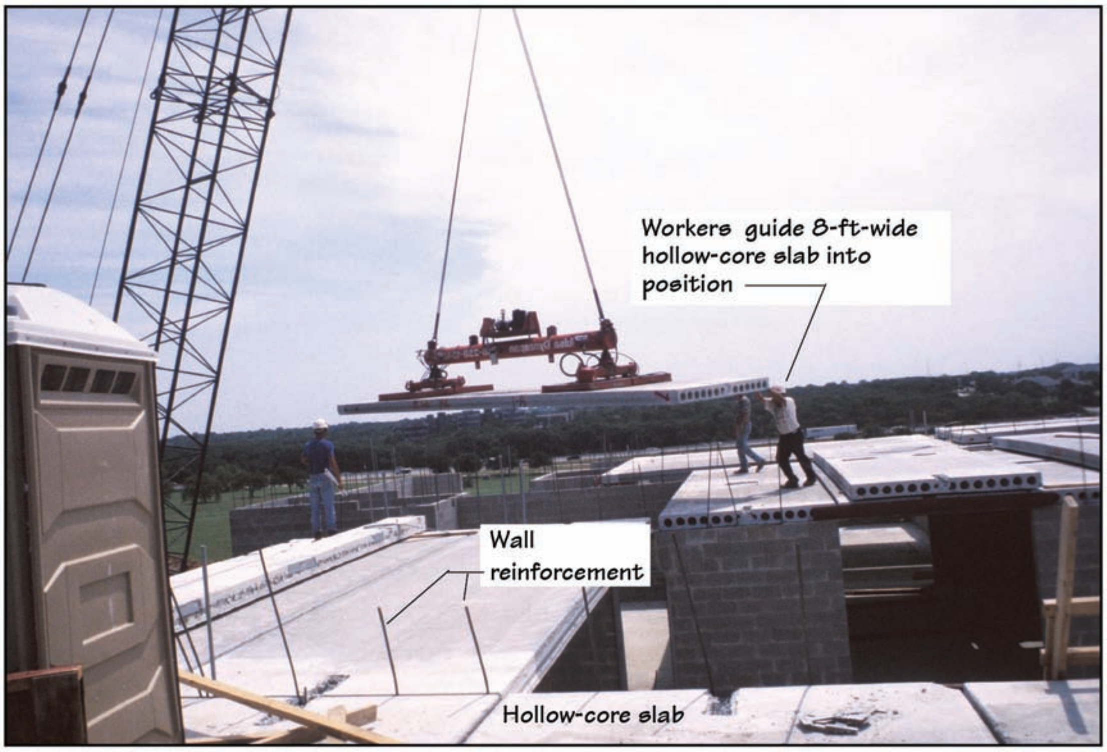

Workers guide 8-ft-wide hollow-core slab into position
Wall reinforcement
Hollow-core slab

FIGURE 26.23(b) An 8-ft-wide precast-concrete hollow-core slab being flown into position. Observe the vertical reinforcement projecting from the lower-level walls.

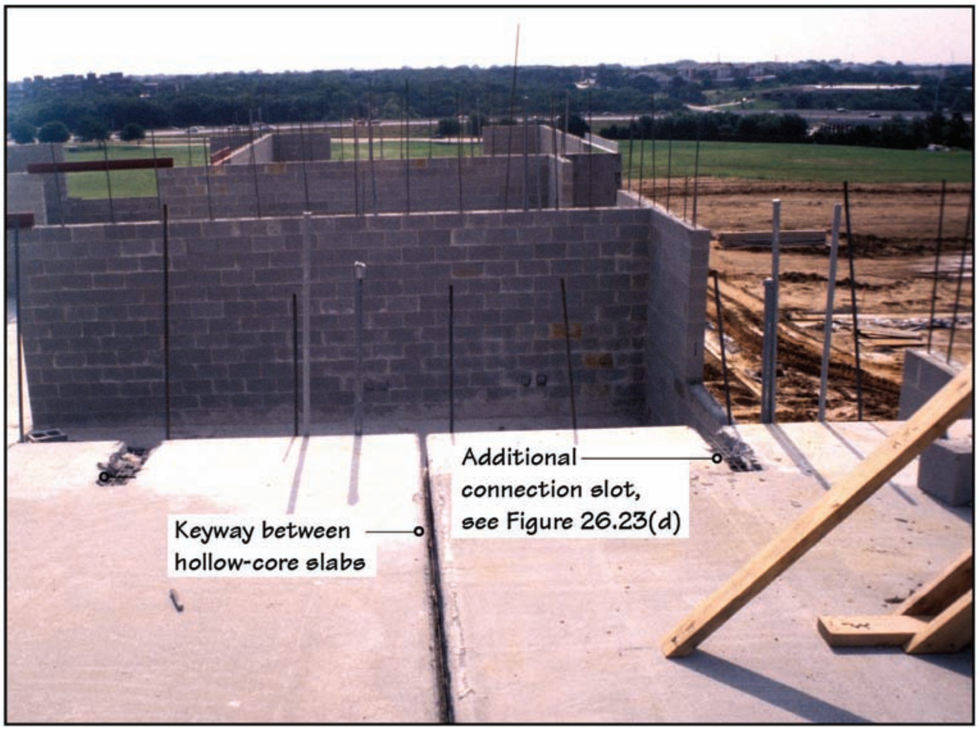

Additional connection slot, see Figure 26.23(d)
Keyway between hollow-core slabs

FIGURE 26.23(c) Keyway between 8-ft-wide hollow-core slabs. Additional connection slots have been provided in the center of each slab. Observe that the floor of plan of the building is a cross-bearing wall plan (see Figure 26.14).

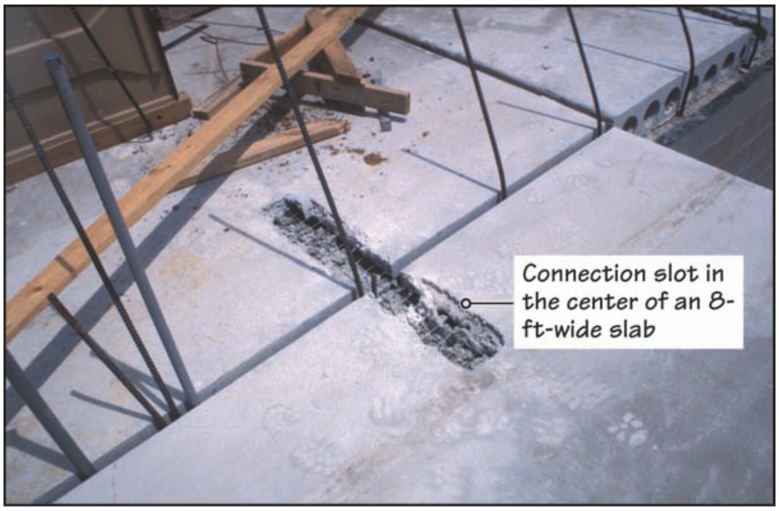

Connection slot in the center of an 8-ft-wide slab

FIGURE 26.23(d) An 8-ft-wide hollow-core slab has a factory-provided slot in the center in order to achieve a connection between the walls and the hollow-core slabs at 4 ft on center.

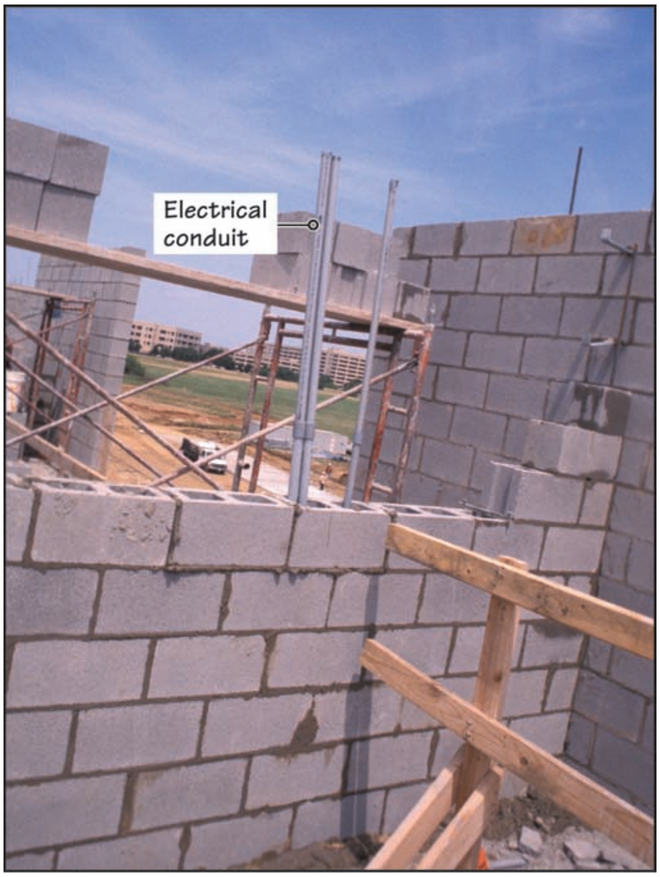


FIGURE 26.23(e) Electrical conduits and other utility lines must be built into walls during construction.

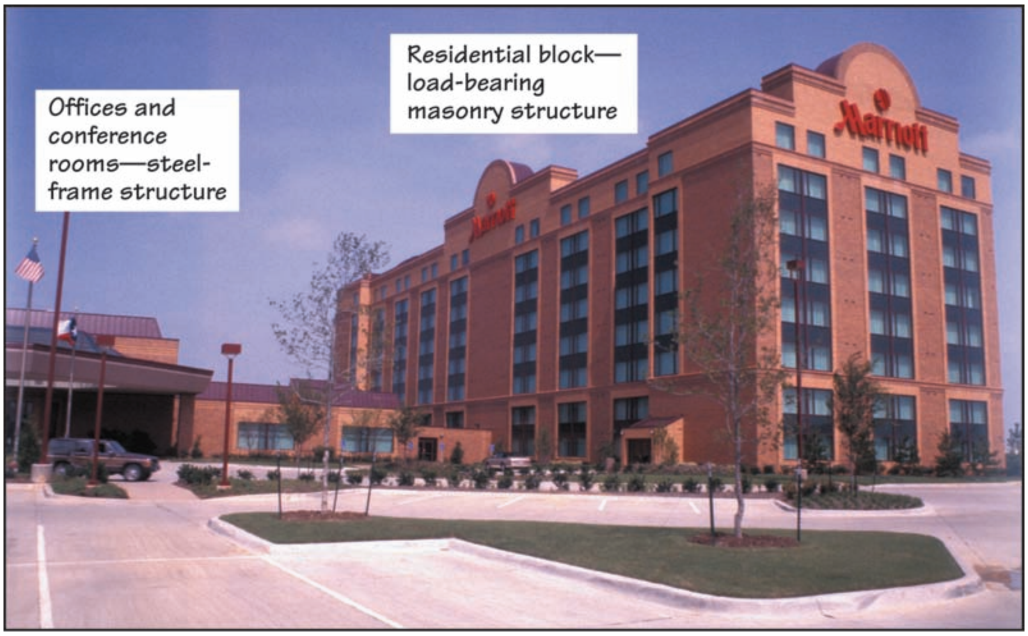


FIGURE 26.23(f) The eight-story hotel residential block with a masonry bearing wall structure (shown under construction in (a) to (e)). The office and conference areas in this building are in steel frame because of their large, unobstructed spaces.

26.7 BEARING WALL AND COLUMN-BEAM SYSTEM

Although masonry bearing wall construction is most suited for mid- to high-rise residential occupancies, as previously described, it is also well-suited to low-rise building types. Chief among them are school and college buildings, offices, shopping centers, and religious buildings.

However, such buildings generally consist of a hybrid construction system, in which all exterior walls are masonry bearing walls and the interior structure is a combination of masonry bearing walls, drywall partitions, and a column-beam frame. The lateral load resistance is generally designed into the masonry walls.

The column-beam frame may consist of cast-in-place concrete or steel. Concrete is better suited because both concrete and concrete masonry have similar properties, causing few differential-movement problems. However, a steel frame is generally more economical and is, therefore, widely used.

Differential-movement problems between steel columns and masonry walls must be considered; they are generally more easily managed in low-rise buildings. Figure 26.24 shows a typical building that combines load-bearing masonry with a steel frame.

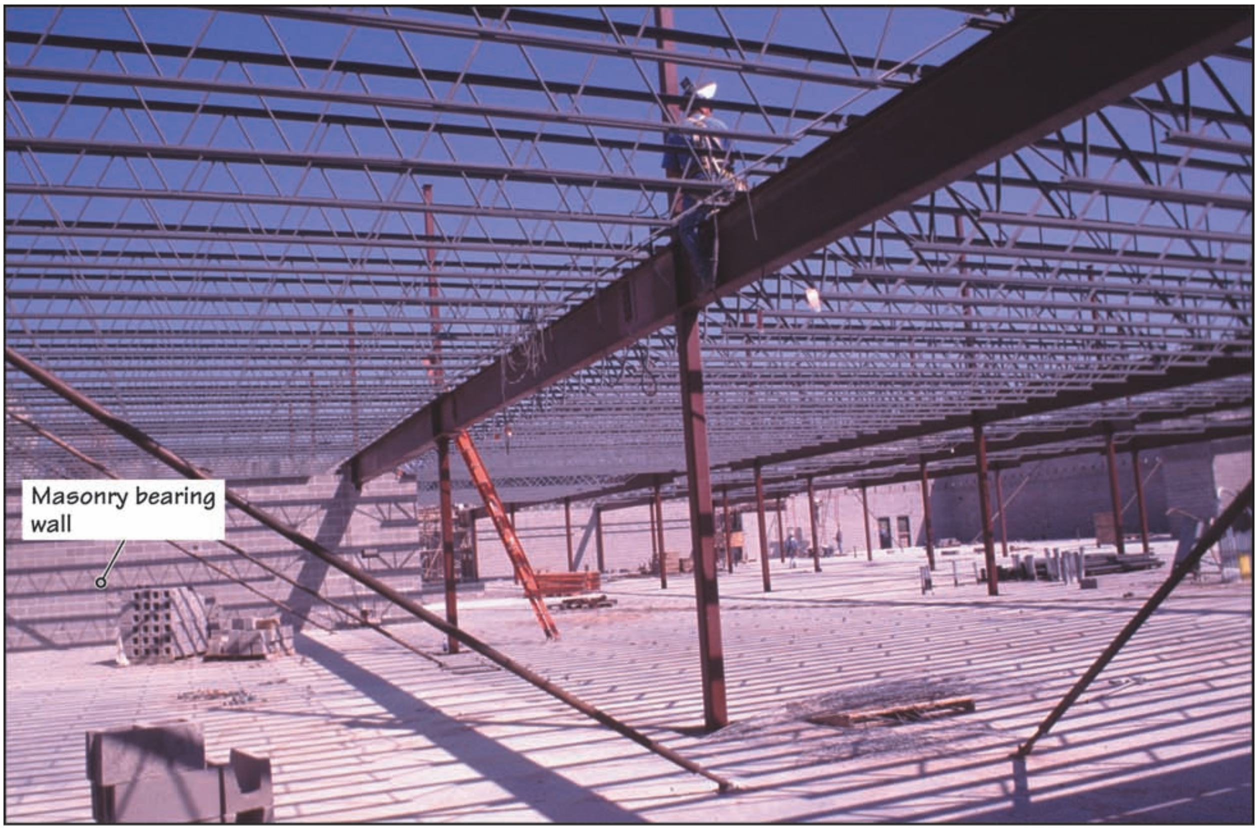


FIGURE 26.24 A school building with exterior load-bearing masonry walls and interior steel frame under construction.

26.8 REINFORCED-CONCRETE BEARING WALL CONSTRUCTION

Site-cast reinforced-concrete bearing walls can be used in place of masonry bearing walls. When used in conjunction with site-cast reinforced-concrete floor slabs, they provide a robust structure because of the inherent continuity between the vertical and horizontal elements of the building.

In other words, the joints between the walls and the floor slabs of a site-cast reinforced-concrete bearing wall structure are tougher than those in masonry wall and precast-concrete hollow-core slab structures. Site-cast-concrete bearing wall structures are, therefore, better able to resist lateral loads. Additionally, site-cast reinforced-concrete walls can seamlessly integrate with a site-cast reinforced-concrete column-beam frame in the case of a hybrid (bearing wall and frame) system.

LOAD-BEARING REINFORCED-CONCRETE MASONRY WALLS WITH TUNNEL FORMS

In general, a site-cast concrete bearing wall structure can be designed with thinner walls than a similar masonry bearing wall structure. As stated in Chapter 22, a a site-cast concrete structure is economical only if the cost of formwork is controlled. A type of formwork that has gained favor in constructing high- and mid-rise reinforced-concrete bearing wall structures is the *tunnel form*, Figure 26.25. A tunnel form consists of prefabricated and collapsible steel forms (of an inverted L-shape) that allow the walls and the overlying floor slabs to be cast simultaneously.

Tunnel forms are generally removed the day following the casting of concrete for a given floor, cleaned and prepared for reuse. Depending on the time required to lay the reinforcement and utility conduits for the walls and floors, a three- to four-day cycle for constructing a floor is typical.

Walls and slabs of virtually any thickness can be constructed by increasing or decreasing the distance between tunnel forms. However, the system is feasible only with a modular and repetitive floor plan, such as that obtained in residential structures. Figure 26.26 shows a mid-rise reinforced-concrete bearing wall hotel building constructed using tunnel forms, and Figure 26.27 shows a corresponding high-rise apartment building.

A reinforced-concrete bearing wall building has the same advantages as a masonry bearing wall building, that is, good sound insulation, high fire resistance, and a mold-free structure.

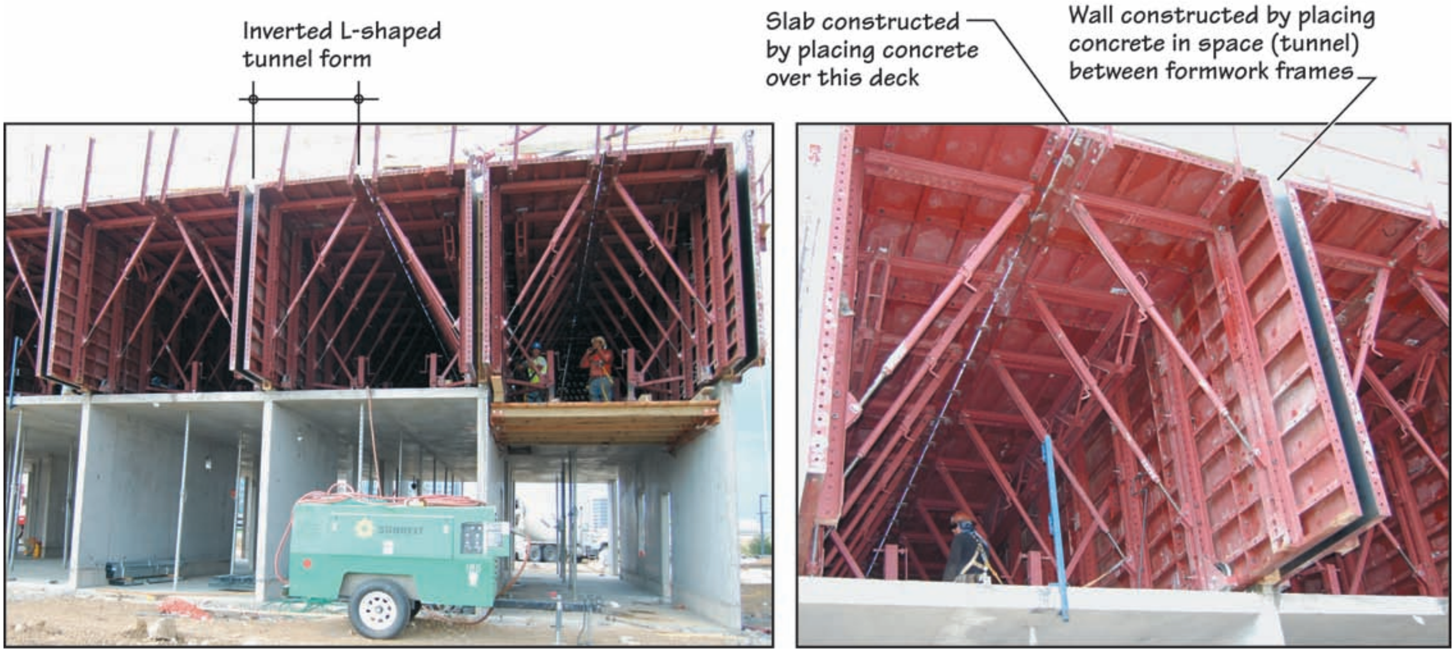

Inverted L-shaped tunnel form
Slab constructed by placing concrete over this deck
Wall constructed by placing concrete in space (tunnel) between formwork frames

FIGURE 26.25 Prefabricated, reusable, and collapsible steel tunnel forms.

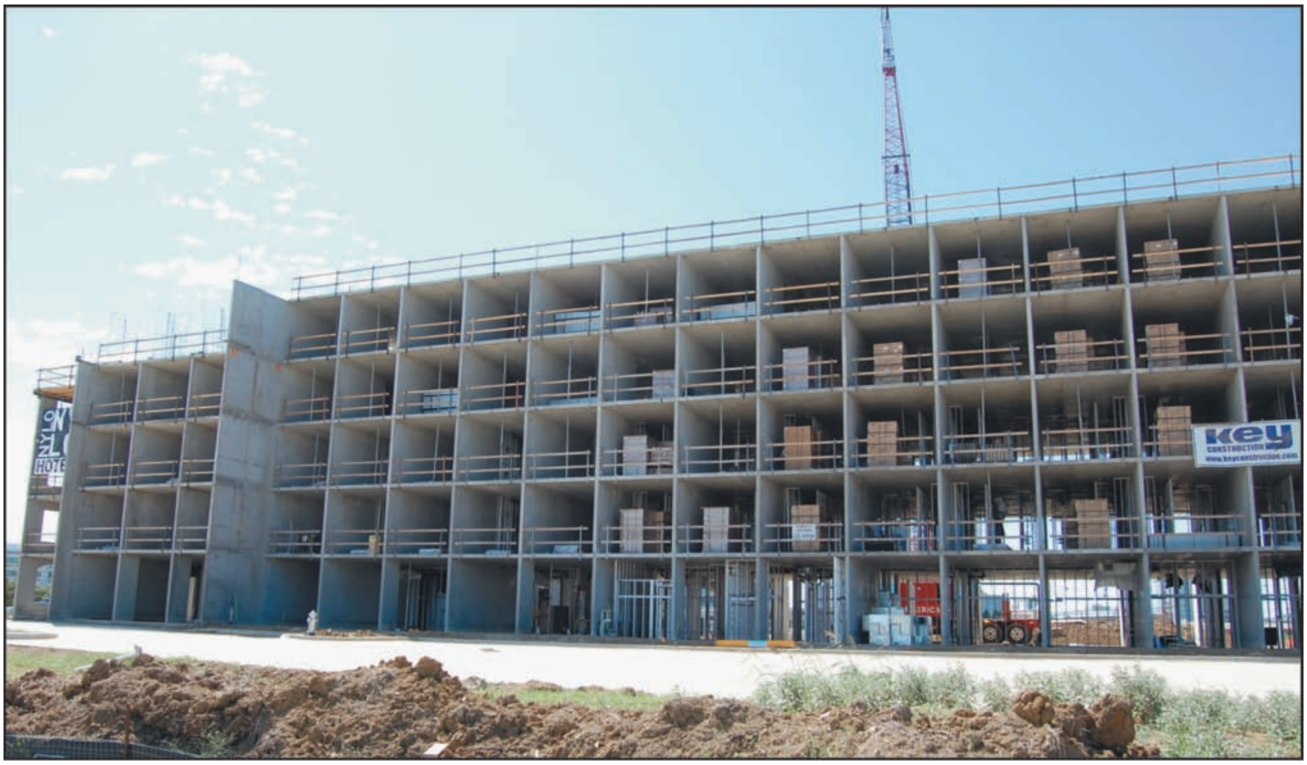


FIGURE 26.26 A five-story hotel building under construction. The structure of the building comprises site-cast reinforced-concrete bearing walls, constructed using steel tunnel forms. The walls and floor slabs of this building are 5 in. thick.

The disadvantages are also the same, the primary disadvantage being the inflexibility in spatial organization. Like their masonry counterpart, exterior site-cast concrete walls generally require a water-resistive cladding.

LOAD-BEARING REINFORCED-CONCRETE BEARING WALLS WITH INSULATED CONCRETE FORMS

Expanded polystyrene insulation can be used as permanent formwork to construct load-bearing reinforced-concrete walls (see Figure 5.40 Principles in Practice, Chapter 5). Because the forms are made of insulation, they are called *insulated concrete forms* (ICFs) and are useful only for constructing the exterior walls. Therefore, the interior structure of an ICF building consists of wood or steel frame (similar to that of Figure 26.24).

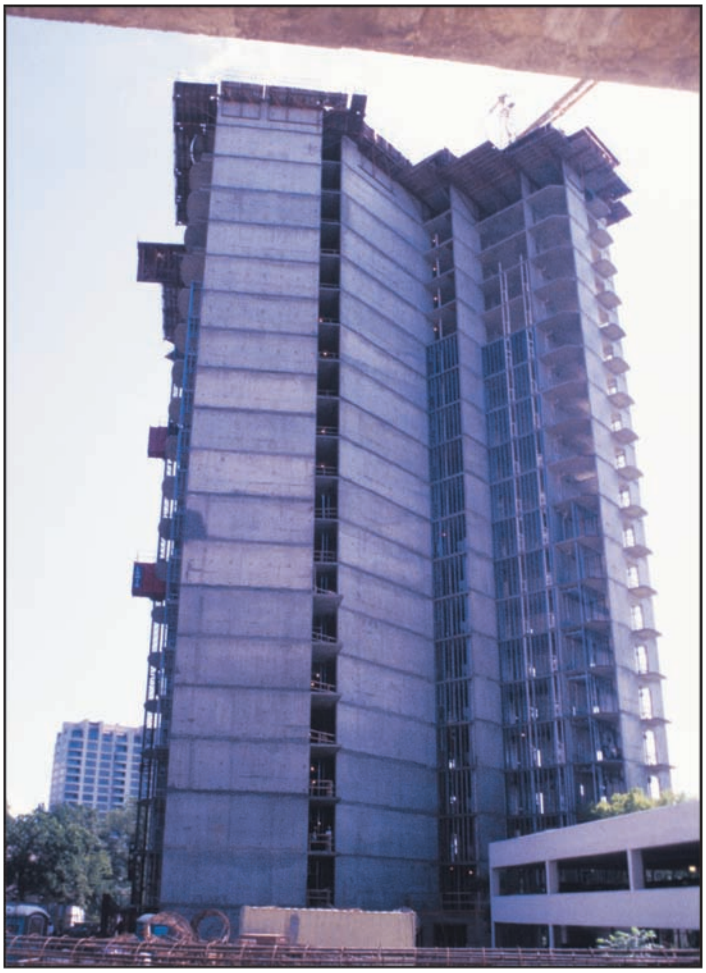


FIGURE 26.27 A 22-story apartment building under construction. The structure of the building comprises site-cast reinforced-concrete bearing walls, constructed using steel tunnel forms. The walls and floor slabs of this building are 6 in. thick.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

14. The commonly used floor system in high-rise and mid-rise masonry bearing wall buildings in North America is
- **a.** cast-in-place reinforced-concrete slabs.
- **b.** precast-concrete hollow-core slabs.
- **c.** precast-concrete double-tee units.
- **d.** all of the above.
- **e.** none of the above.

15. The keyway between precast-concrete hollow-core slabs runs perpendicular to the bearing walls.
- **a.** True
- **b.** False

16. The keyway between precast-concrete hollow-core slabs is generally
- **a.** grouted.
- **b.** reinforced with horizontal steel dowels.
- **c.** reinforced with T-shaped steel dowels.
- **d.** (a) and (c).
- **e.** (a) and (b).

17. Where the cutting of masonry units is discouraged, the wall dimensions are based on the masonry module. The module used in CMU walls is
- **a.** 4 in.
- **b.** 8 in.
- **c.** 12 in.
- **d.** 16 in.
- **e.** none of the above.

18. The clear height of openings in CMU walls is
- **a.** $\frac{3}{8}$ in. greater than the multiples of the masonry unit module.
- **b.** $\frac{3}{8}$ in. less than the multiples of the masonry unit module.
- **c.** $\frac{1}{8}$ in. greater than the multiples of the masonry unit module.
- **d.** $\frac{1}{8}$ in. less than the multiples of the masonry unit module.
- **e.** none of the above.

19. In high-rise residential buildings built with site-cast reinforced-concrete bearing walls using tunnel forms, the floors and roofs are generally constructed of
- **a.** steel joists and metal deck.
- **b.** wide-flange steel beams and metal deck.
- **c.** precast-concrete hollow-core slabs.
- **d.** lumber joists and beams.
- **e.** none of the above.

20. The formwork used in constructing site-cast reinforced-concrete walls and floors simultaneously consists of
- **a.** horizontal and vertical plywood forms.
- **b.** sheet steel gang forms.
- **c.** sheet steel tunnel forms.
- **d.** insulating concrete forms.
- **e.** none of the above.

21. Insulating concrete forms can only be used for
- **a.** interior load-bearing walls.
- **b.** interior or exterior non-load-bearing walls.
- **c.** exterior load-bearing walls more than 10 in. thick.
- **d.** all of the above.
- **e.** none of the above.

26.9 REINFORCED-CONCRETE TILT-UP WALL CONSTRUCTION

A system of construction that competes with masonry bearing wall system, and is often selected as an alternative to it, is the reinforced-concrete tilt-up wall system. In this system, the walls are precast on site as horizontal panels, generally over a concrete slab-on-ground, which also serves as the first floor slab of the building. A form-release agent is used between the slab-on-ground and the wall panels.

If the first floor slab of the building is too small to accommodate the precasting of all wall panels (i.e., a building with a small footprint and relatively tall walls), stack casting of panels is used. In stack casting, one or more panels are cast on the lower panel, using a form-release agent between panel surfaces.

In situations where the first floor of the building is constructed on an elevated slab because the soil is unsuitable for supporting it directly on the ground (such as where the ground comprises expansive soil or dense rock), the panels are cast on a casting slab-on-ground, constructed specifically for the purpose. This slab is subsequently broken and the concrete recycled for use as aggregate for the subgrade in roads and pavements.

Figure 26.28 shows tilt-up wall panels cast on a casting slab. The formwork for the perimeter of panels and openings within the panels consists of 2-by lumber members, which gives formwork economy. It is because of the use of standard 2-by lumber members as forms that the thickness of tilt-up wall panels is generally 5-$\frac{1}{2}$ in., 7-$\frac{1}{4}$ in., or 9-$\frac{1}{4}$ in.

Before placing concrete in panel formwork, all panel reinforcement, lifting hardware, and steel embeds for attaching the floor and roof structural members to the walls are positioned in required locations, Figure 26.29. Form liners (if used) and the inserts for reveals and other surface relief elements are placed on the casting slab before laying panel reinforcement, Figure 26.30.

After the panels have been cast and the concrete has gained the required strength (typically a week or longer after casting), they are lifted with a crane from their horizontal position and placed in their intended locations as wall panels, Figures 26.31and 26.32. Because of the limited lifting capacity of the cranes and the stresses produced in the wall during the lift, tilt-up panels cannot be too high or too long. A concrete tilt-up wall system is, therefore, limited to low-rise buildings, generally up to a maximum of 50 ft high (one to four stories). The walls in a typical tilt-up building consist of several panels, each panel extending to its full height. (Buildings taller than four stories, with upper-story panels bearing on the lower-story panels, have been constructed but are rare.)

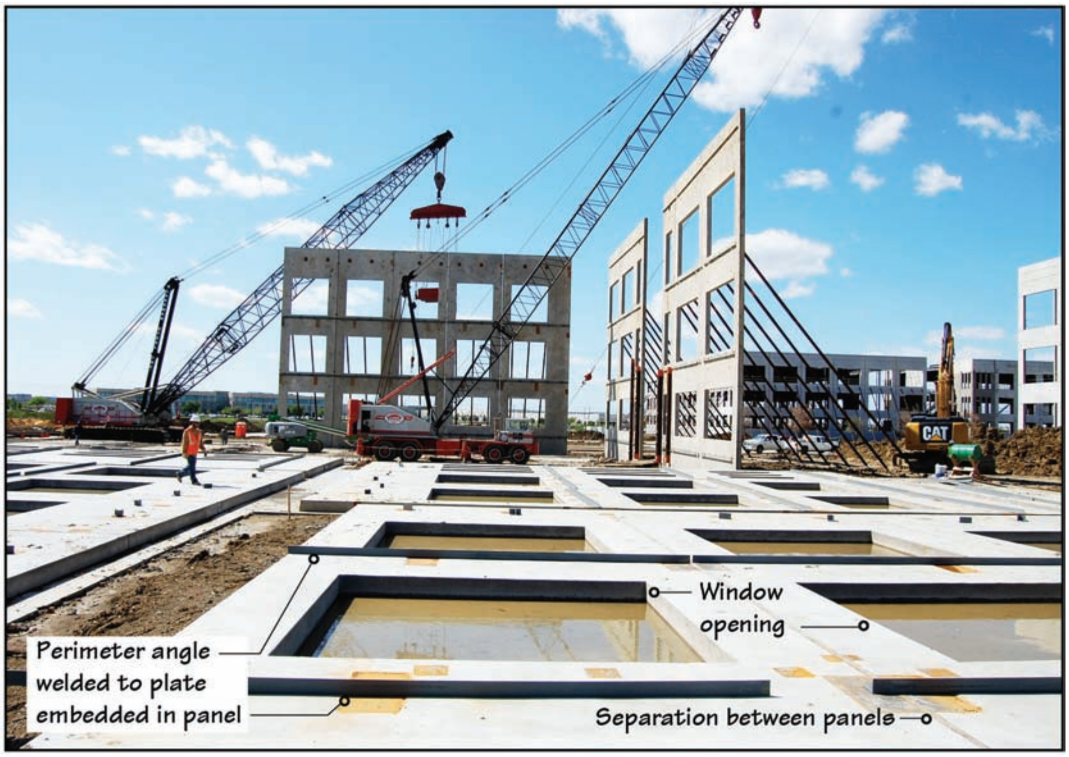

CAT
Window opening
Perimeter angle welded to plate embedded in panel
Separation between panels

FIGURE 26.28 Three-story reinforced-concrete tilt-up wall panels cast over a casting slab, which is broken after all panels have been cast and erected. The broken concrete is used as aggregate in the subgrade for roads and pavements. Shown in the background are cranes that lift the panels and erect them in their intended locations. Various roof and floor support items are welded to embeds in a panel before the lifting operation.

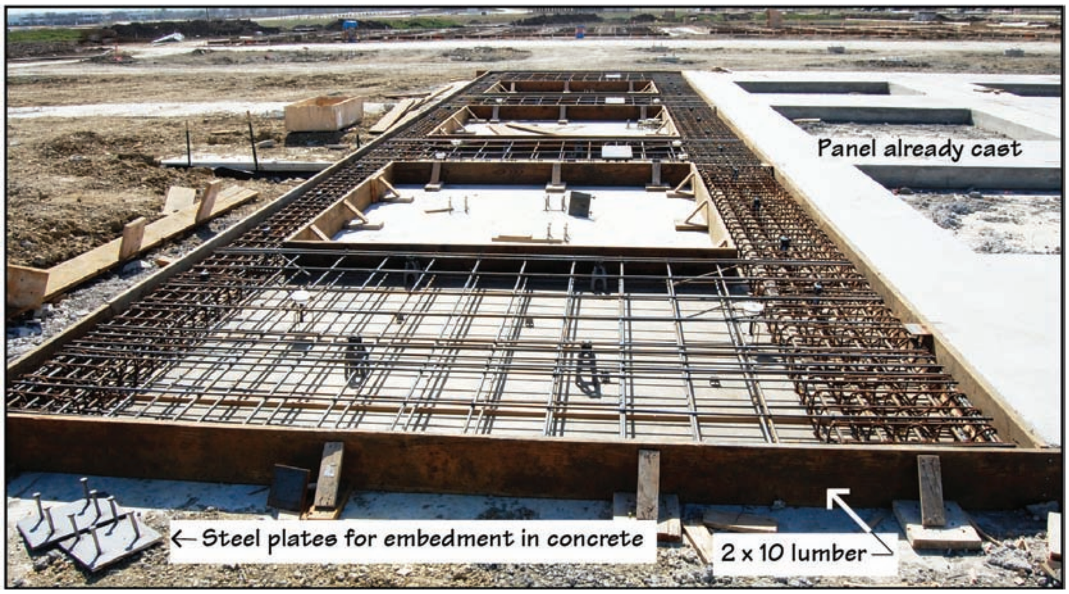

Panel already cast
←Steel plates for embedment in concrete
2 x 10 lumber

FIGURE 26.29 Formwork and reinforcement in a three-story reinforced-concrete tilt-up wall panel ready to receive concrete. The formwork consists of 2-by lumber members (2 × 10 in this case). The heavy reinforcement at the ends of the panel is because it will be supported at two ends over a pad or a drilled pier footing. All steel plates to which floor and roof support elements will be welded are tied to the reinforcing bars at the requited locations. Seen in the foreground are two such embed plates.

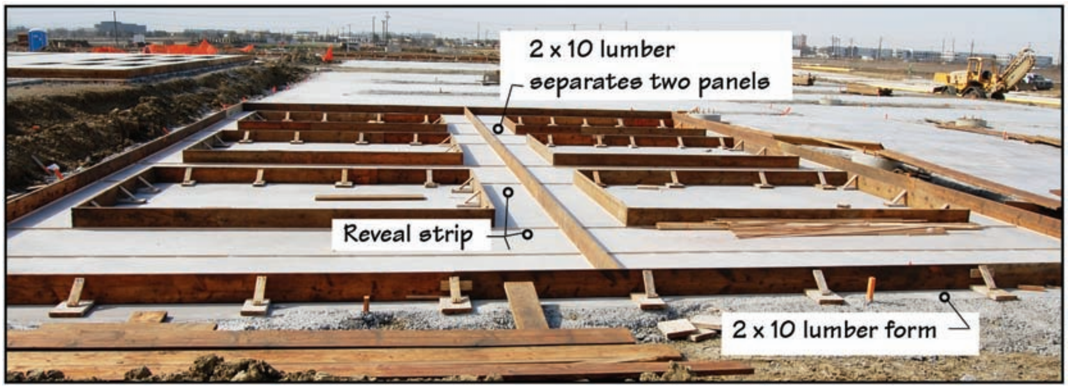

2 x 10 lumber
separates two panels
Reveal strip
2 x 10 lumber form

FIGURE 26.30 Formwork for three-story tilt-up wall panels before the laying of panel reinforcement. Removable wood or plastic strips that create reveals (recesses in concrete that falsely appear as joints) and form liners, if any, are placed before the laying of reinforcement.

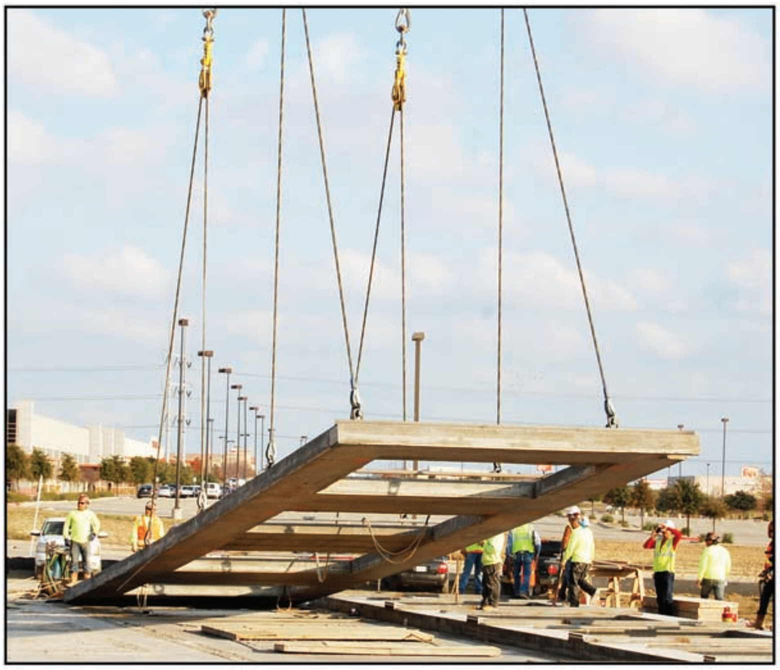


FIGURE 26.31 A four-story panel being tilted up. The panel will be moved to its intended location as shown in Figure 26.32.

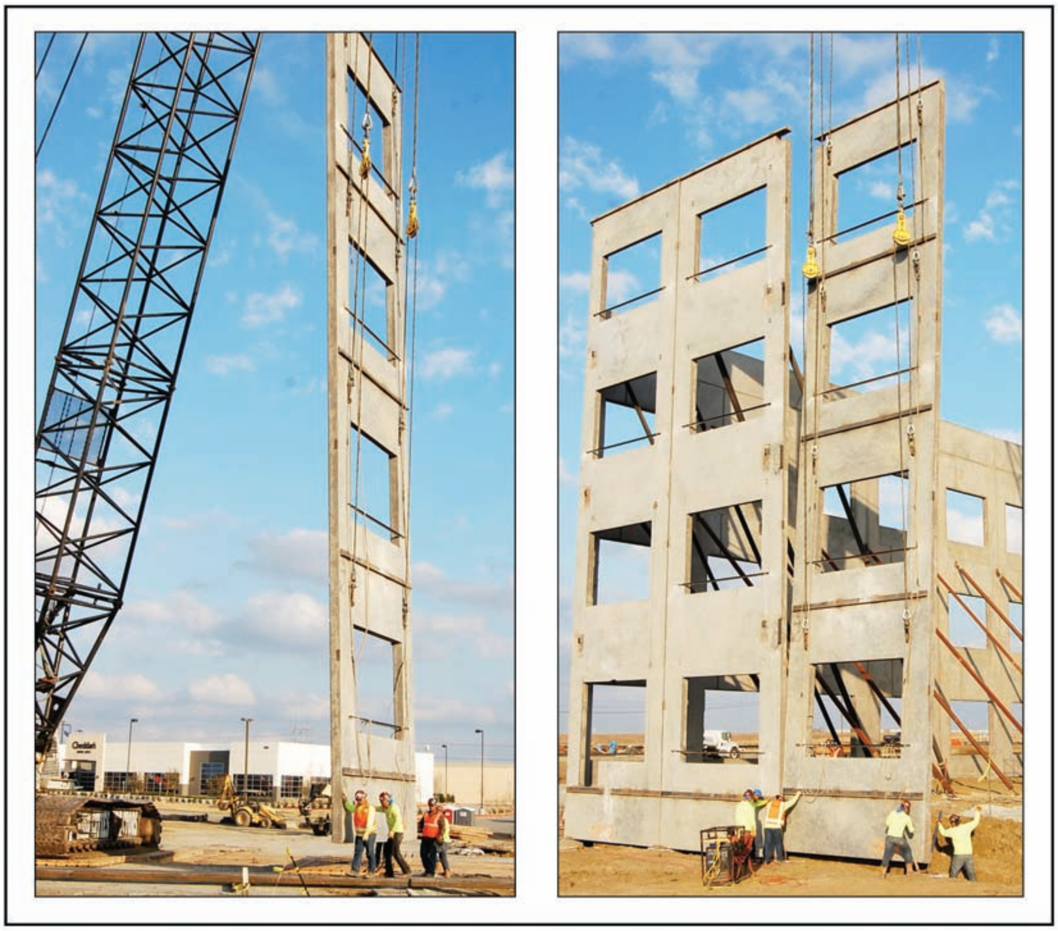


FIGURE 26.32 The four-story panel of Figure 26.31 being brought into its intended location and placed over the footing.

PANEL BRACES

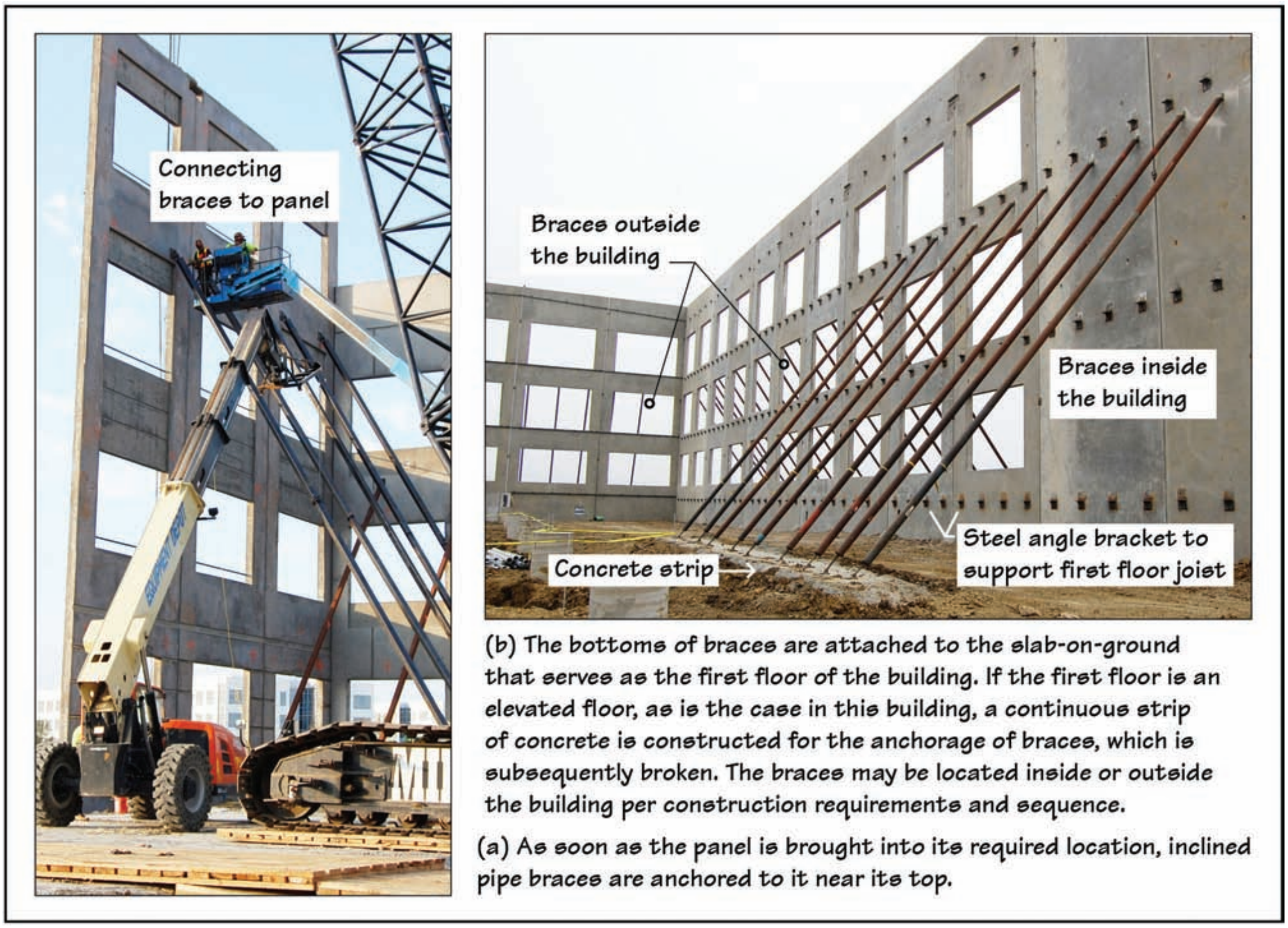
After a panel has been brought into its intended position, it is anchored to steel pipe braces, which are typically inclined 45° to 55° with the horizontal. The top anchorage is approximately one-quarter to two-thirds of the panel height, Figure 26.33(a). The bottom of a brace is anchored to the interior slab-on-ground. A building without an interior slab-on-ground, that is, whose first floor is an elevated floor, the bottom of a brace is anchored to a concrete pad or a concrete strip specially constructed for the purpose, Figure 26.33(b). Referred to as *deadman*, the concrete pad or strip is broken after the braces are removed.

The connection of the brace at its bottom is extremely critical because almost all brace failures occur here. The braces hold the panel plumb and resist the lateral loads during the building's construction. Supporting a panel one-quarter to two-thirds from its top (instead of the very top) reduces bending stresses in the panel caused by lateral loads. This is similar to a uniformly loaded, simply supported beam that has reduced stresses if it is provided with a small overhang.

The braces may be located either inside the building or outside, as shown in Figure 26.33(b). Interior placement of braces may interfere with the interior structural elements because most tilt-up wall buildings are hybrid structures in which the exterior walls are load-bearing tilt-up walls and the interior structure consists of steel columns and beams. The roof and floor structure may consist of open-web steel joists or wide-flange steel beams as needed, Figure 26.34. Note that the braces are removed only after the building has attained lateral stability provided by the connections of panels with floors, roof, and the footings that support the panels.

CONCRETE STRENGTH IN PANELS AND PANEL THICKNESS

The strength of concrete used for panels is typically 4,000 psi. The thickness of tilt-up wall panels is determined by structural (strength and durability) considerations. Although bending stresses in panels, caused by in-service lateral loads and eccentricity of dead loads, are important, the primary factor that determines the thickness of panels is the stresses caused during the lifting of panels. The structural design of panels must ensure that the tensile stresses during lifting are below the concrete's allowable tensile strength, which is generally


Connecting braces to panel
Braces outside the building
Braces inside the building
Concrete strip
Steel angle bracket to support first floor joist

(b) The bottoms of braces are attached to the slab-on-ground that serves as the first floor of the building. If the first floor is an elevated floor, as is the case in this building, a continuous strip of concrete is constructed for the anchorage of braces, which is subsequently broken. The braces may be located inside or outside the building per construction requirements and sequence.

(a) As soon as the panel is brought into its required location, inclined pipe braces are anchored to it near its top.

FIGURE 26.33 **(a)** Immediately after its placement in its intended location, the panel is anchored to steel pipe braces approximately one-quarter to two-thirds from its top. **(b)** A strip of concrete slab to anchor braces inside the building. A similar strip is provided for braces located outside the building.

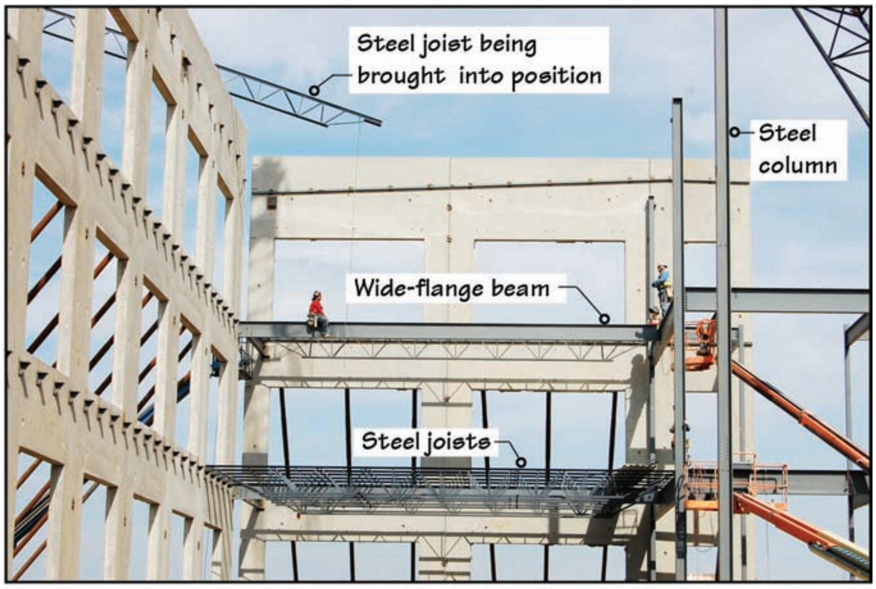

Steel joist being brought into position
Steel column
Wide-flange beam
Steel joists

FIGURE 26.34 In most tilt-up wall buildings, the tilt-up walls are used as exterior bearing walls while the interior structure consists of structural steel frame, that is, steel columns, wide-flange beams, and (or) steel joists.

10% to 12% of the compressive strength of concrete used in panels. Thus, for a 4,000-psi concrete, it is approximately 400 psi to 500 psi. Keeping the tensile stress in concrete within its allowable stress ensures that the concrete will not crack during lifting.

The cracking of concrete is not only aesthetically undesirable, but it also affects the durability of the panel by allowing water and water vapor to penetrate into it, causing the corrosion of steel, and rendering concrete vulnerable to freeze-thaw action. A greater panel thickness and higher-strength concrete reduces concrete cracking and improves panel's durability. It also reduces stresses caused by thermal expansion and contraction of panels.

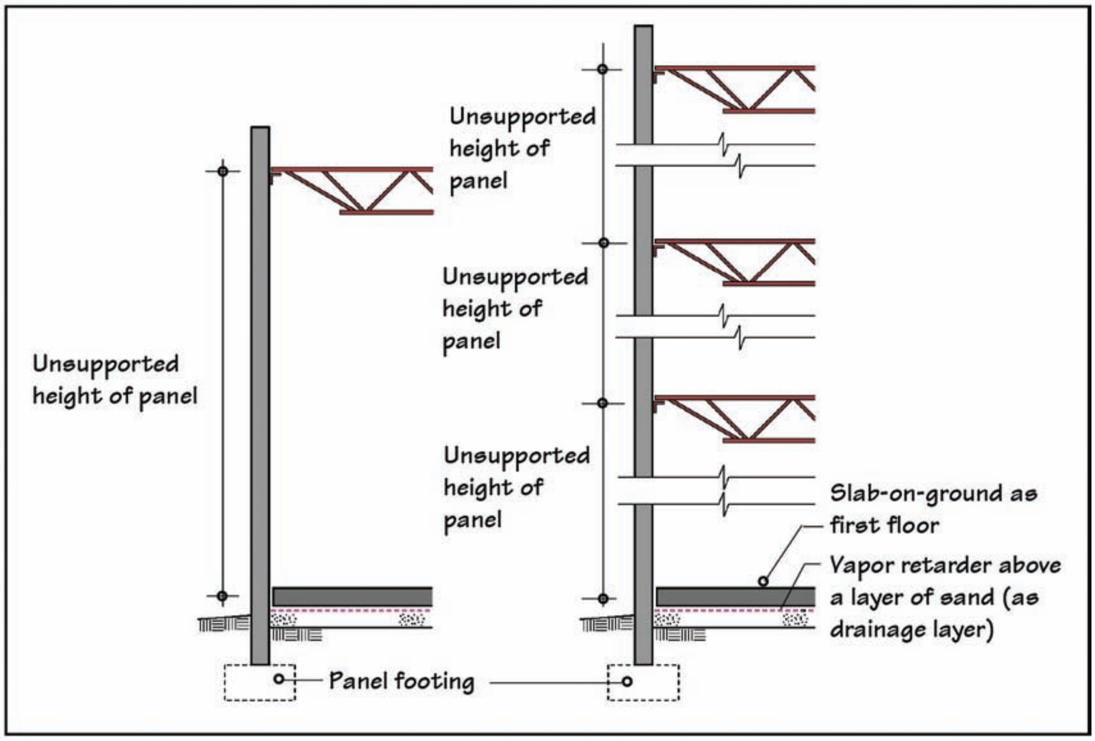
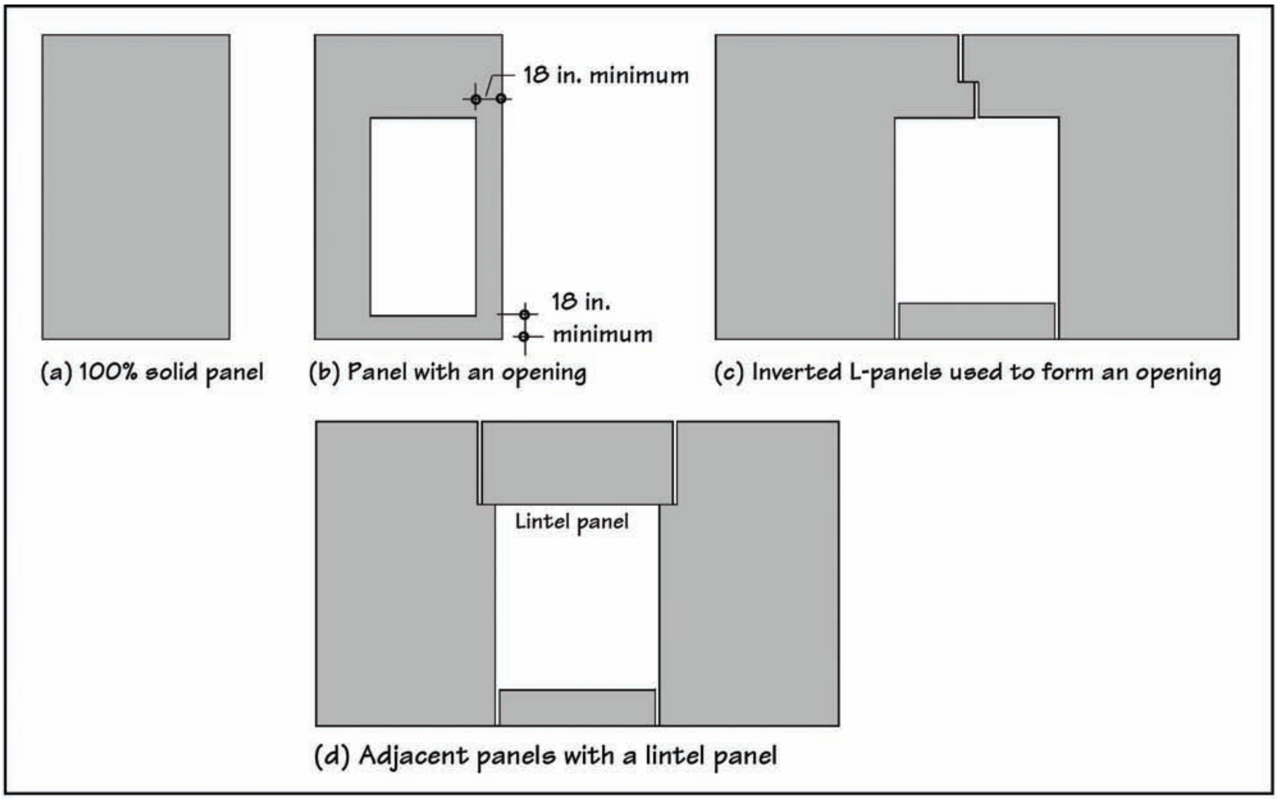

Unsupported height of panel
Unsupported height of panel
Unsupported height of panel
Unsupported height of panel
Slab-on-ground as first floor
Vapor retarder above a layer of sand (as drainage layer)
Panel footing

FIGURE 26.35 The primary factor that determines the thickness of a tilt-up panel is the tensile stress caused in concrete during lifting. Among other factors that determine panel thickness is the unsupported height of the panel, defined as the distance between supports, that is, between the footing and the roof in a single-story building. For a multistory building, the largest unsupported height is taken into account.

The minimum panel thickness is 5-$\frac{1}{2}$ in., but 7-$\frac{1}{4}$-in.-thick panels for a one-story building and 9-$\frac{1}{4}$-in.-thick for up to four stories is common. Panel thickness is also a function of the maximum unsupported height of a panel. Note that the panel is laterally supported at footing, floors, and the roof. Therefore, the unsupported height is the distance between these elements, Figure 26.35.

SHAPE AND MAXIMUM SIZE OF PANELS

A tilt-up wall panel may be with or without openings. Openings in a panel represent areas of weakness that can damage the panel during lifting. Generally, a minimum wall width of 18 in. is required around an opening, Figure 26.36(b). Large openings may be created by using either two inverted L-panels or a lintel panel that bears on the two adjacent panels, Figures 26.36(c) and (d).


18 in. minimum
18 in. minimum
Lintel panel

(a) 100% solid panel (b) Panel with an opening (c) Inverted L-panels used to form an opening

(d) Adjacent panels with a lintel panel

FIGURE 26.36 Shapes of typical tilt-up wall panels.

Structural steel members (angles or wide-flange sections) are used temporarily to strengthen an opening near a narrow panel width (jamb area). Referred to as *strongbacks*, they are anchored to a panel before lifting and are removed after the panel's erection, Figure 26.37. However, anchoring the strongbacks to panels and removing them later adds to the cost of construction, and is used only if the width of solid portion near the opening cannot be increased.

The maximum size of panels depends on the lifting capacity of the crane available in the area. Architects must obtain this information before deciding to panelize the walls and working on building elevations and other related details.

SLAB-ON-GROUND, CONCRETE STRENGTH, AND REINFORCEMENT

The Tilt-up Concrete Association (TCA) recommends a minimum concrete strength of 3,000 psi for the slab. However, the use of 4,000-psi concrete is customary. The thickness of the slab-on-ground in a tilt-up wall building depends on its occupancy and the load imposed on it during construction. Generally, the load on the slab from construction traffic is greater than that of the occupancy load, Figure 26.38. A minimum slab thickness of 5 in. is generally recommended regardless of the loads on the slab. Note that the strength of the slab is directly proportional to the square of its thickness. Thus, a 6-in.-thick slab is 44% stronger than a 5-in-thick slab because $\left[\frac{6}{5}\right]^2 = 1.44$. In other words, a small increase in slab thickness yields a relatively larger increase in its strength.

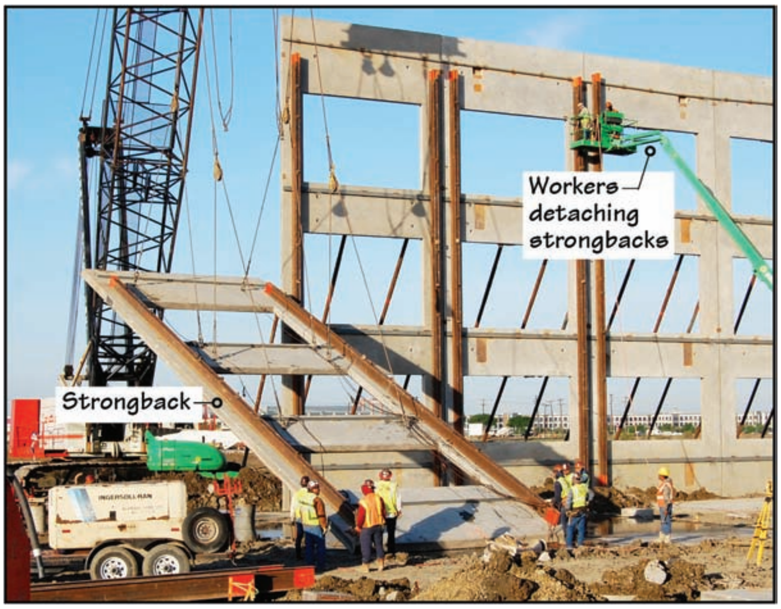


FIGURE 26.37 Panels with narrow jambs are strengthened with wide-flange sections anchored to them, referred to as *strongbacks*, which are detached after the panel has been erected.

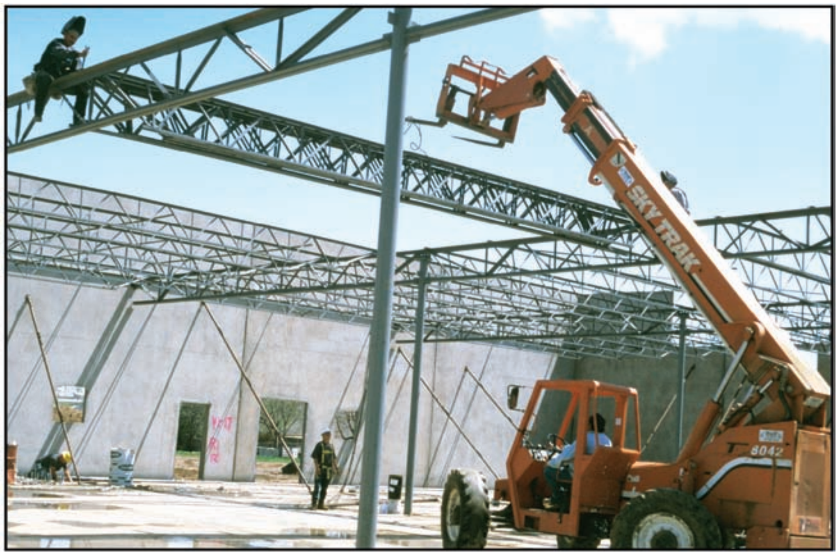


FIGURE 26.38 Because of the use of heavy equipment that is supported on the slab during construction, the load on a concrete slab-on-ground in a tilt-up wall building is generally larger than in-service live load.

FOUNDATIONS FOR TILT-UP WALLS

The foundations for tilt-up wall panels generally consist of the following types, Figure 26.39:

- Continuous strip footing
- Isolated pad footing
- Drilled pier footing

On a strip footing, a panel has a continuous bearing. On an isolated pad or pier footing, the panel bears only at its ends, carrying the load as a deep beam between the footings. A drilled pier footing is generally used in weak or expansive soils (see Chapter 12). The bottom ends of panels, supported by pad or drilled pier footings, are typically enclosed within steel channel sections that provide a strong bearing support and allow the panels to be welded to steel plates embedded in the footings, Figure 26.40(a).

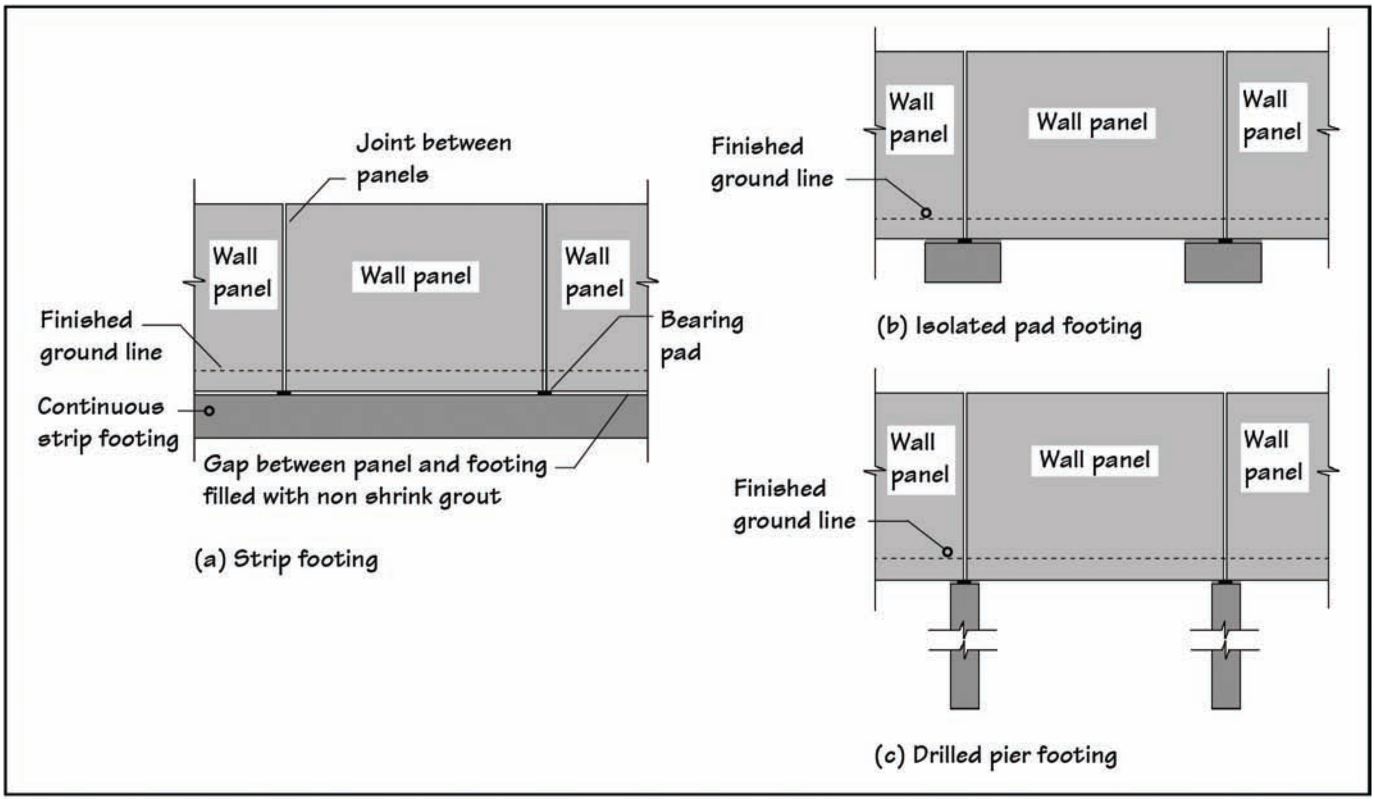

Joint between panels
Wall panel
Wall panel
Wall panel
Finished ground line
Bearing pad
Continuous strip footing
Gap between panel and footing filled with non shrink grout
(a) Strip footing
Wall panel
Wall panel
Wall panel
Finished ground line
(b) Isolated pad footing
Wall panel
Wall panel
Wall panel
Finished ground line
(c) Drilled pier footing

FIGURE 26.39 Commonly used footing alternatives for tilt-up wall panels.

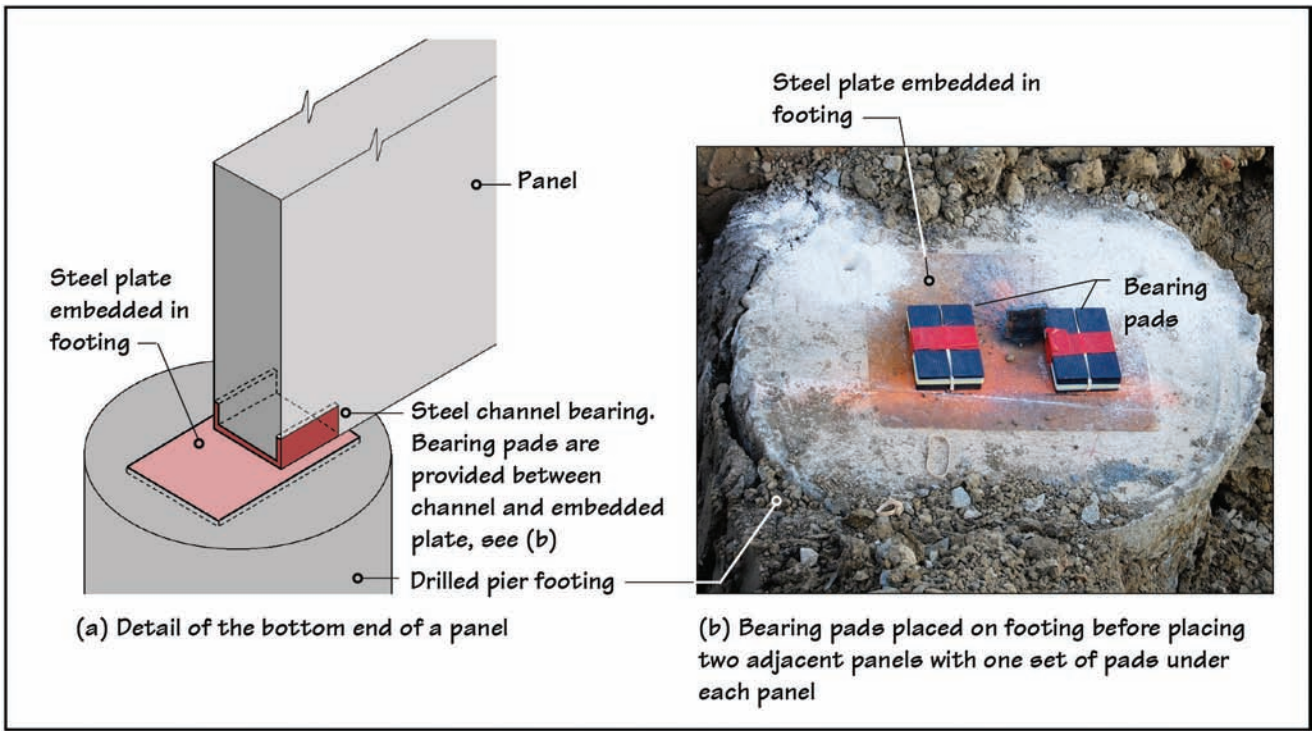

Panel
Steel plate embedded in footing
Steel channel bearing. Bearing pads are provided between channel and embedded plate, see (b)
Drilled pier footing
(a) Detail of the bottom end of a panel
Steel plate embedded in footing
Bearing pads
(b) Bearing pads placed on footing before placing two adjacent panels with one set of pads under each panel

FIGURE 26.40 **(a)** A panel supported on a drilled pier or pad footing is provided with steel channel bearing sections at both ends to reduce bearing stresses in the panel and the footing. This also allows the welding of the channel to steel plate embedded in footing (see Figure 26.41). **(b)** The panel ends bear on high-strength plastic pads that allow the leveling of panels.

Regardless of the type of footing, the bottom of the panel is 1 in. to 2 in. above the top of the footing. This gap is produced by setting the panel on high-strength bearing pads, generally one set of bearing pads at each end of the panel, Figure 26.40(b). The bearing pads help to level the panel and ensure that it is set at the required elevation. A panel is released from the crane only after it has been leveled and anchored to braces.

Two adjacent panels generally bear on the same footing pad or drilled pier, as seen in Figures 26.40(b) and 26.41. The gap between panels and the footings is filled with high-strength, nonshrink grout so that in the completed building, the load from the panel is transferred over a greater area than the area of the bearing pads.

26.10 CONNECTIONS IN A TILT-UP WALL BUILDING

Connections between various elements of a tilt-up wall building are critical for the overall structural integrity of the building. The following four connections are important:

- Between a panel and the footing
- Between a panel and the slab-on-ground
- Between a panel and the floor, and between a panel and the roof
- Between adjacent panels

CONNECTION BETWEEN A PANEL AND FOOTING

Most panels in a tilt-up wall building, because of their size and weight, are not subjected to an overturning moment. So, they are not subjected to an uplift force at their ends. Consequently, a positive connection between a panel and footing is generally unnecessary. However, the connection must resist shear forces caused by lateral loads (in-plane shear, i.e., sliding parallel to the panel and out-of-plane shear—sliding perpendicular to the panel). This is generally accomplished by welding the panel to the plate embedded in the footing, Figure 26.41.

CONNECTION BETWEEN SLAB-ON-GROUND AND TILT-UP WALL PANELS

The connection of a panel with a slab-on-ground is generally provided with a continuous strip of concrete, referred to as the *closure strip*, Figure 26.42. A closure strip is a 5-ft- to 6-ft-wide strip adjoining the panels that is cast after all panels have been erected, while the rest of the slab is cast before the erection of the panels. Bent reinforcement dowels, as part of the reinforcement in the panel, are straightened and lap spliced with the reinforcement projecting from the slab into the closure strip.

Finally, concrete is placed in the closure strip and finished to match the rest of the slab. This connection utilizes the frictional resistance between the floor slab and the subgrade to provide resistance to lateral loading. Bent dowels can be replaced with dowels inserted into the holes drilled into the panel after its erection and epoxy grouting the holes.

An alternative to the closure strip is to cast the entire slab-on-ground up to the inside face of the panel (to be erected) with steel plates embedded in the slab. After the panels have been erected, they are connected to the slab with weld plates, Figure 26.43. This eliminates casting and finishing the slab in two stages.

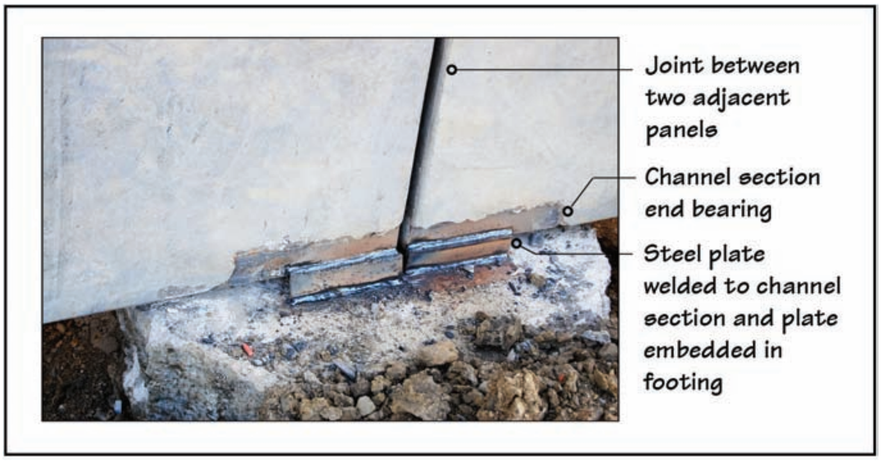
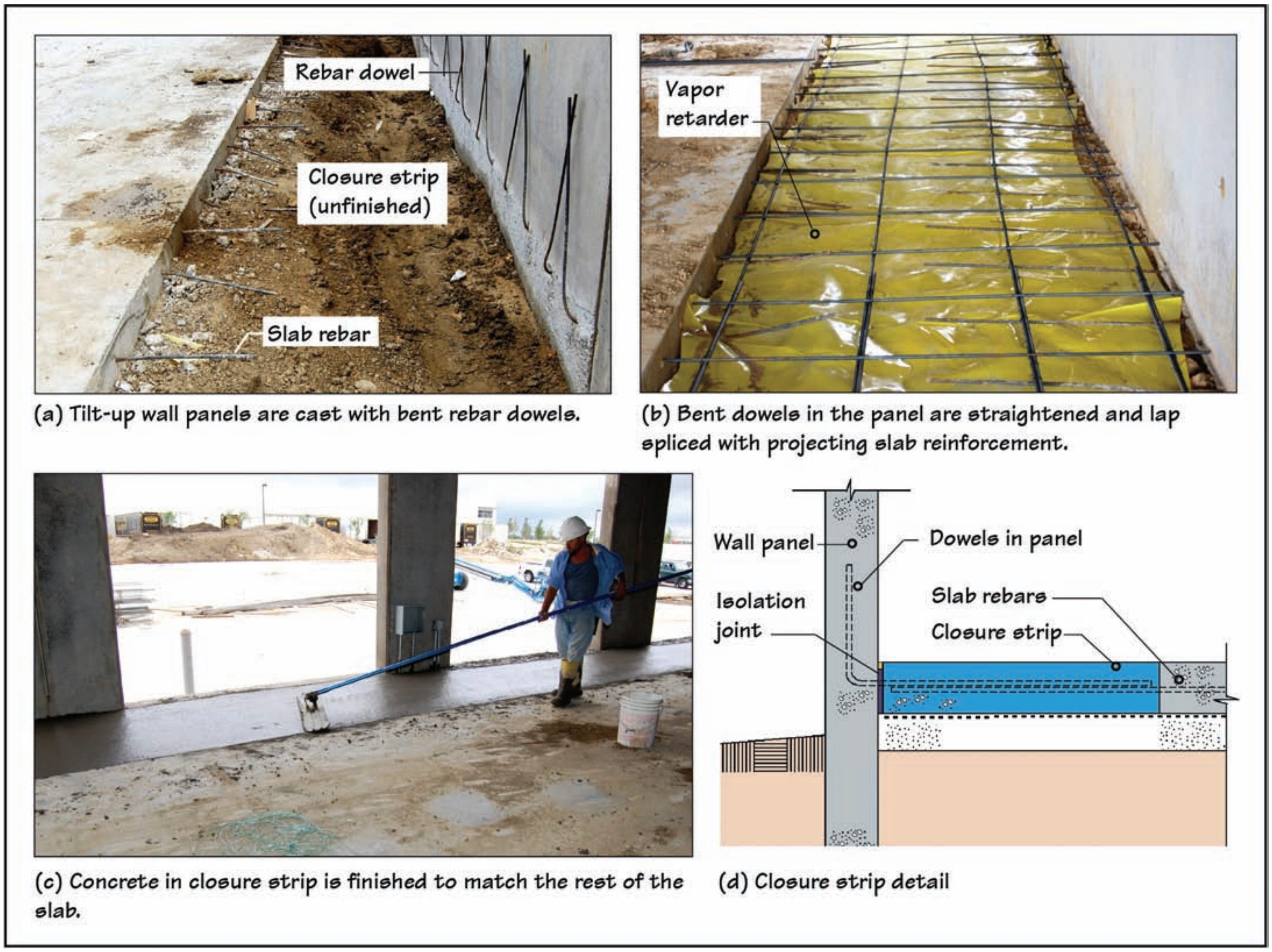

Joint between two adjacent panels
Channel section end bearing
Steel plate welded to channel section and plate embedded in footing

FIGURE 26.41 A typical detail of connection between panel and footing. The steel members are painted and covered with concrete for protection against corrosion.



(a) Tilt-up wall panels are cast with bent rebar dowels.

(b) Bent dowels in the panel are straightened and lap spliced with projecting slab reinforcement.

(c) Concrete in closure strip is finished to match the rest of the slab.

(d) Closure strip detail

FIGURE 26.42 Detail of the connection between tilt-up wall panels and the concrete slab-on-ground using a continuous closure strip.

CONNECTION BETWEEN TILT-UP WALL PANELS AND AN ELEVATED FLOOR OR ROOF

An elevated floor in a tilt-up wall building is framed with steel floor joists or wide-flange beams. Floor joists bear on clip angle brackets welded to embedded plates on the interior face of panels, Figure 26.44. Steel deck is carried by the joists and is welded to them. Where wide-flange sections are used in place of steel joists to support the floors, they are welded to steel plates embedded in panel, Figure 26.45.

The ends of the deck bear on a continuous perimeter angle (that also functions as diaphragm chord), as shown in Figure 26.44. The perimeter angle perpendicular to joists is welded to them while the perimeter angle parallel to joists is welded to plates embedded in the panel. The panels are connected to a floor through reinforcing bar dowels welded to the perimeter angle, Figure 26.46. The dowels welded to perimeter angle get embedded in slab concrete that completes the connection between the panels and the floor.

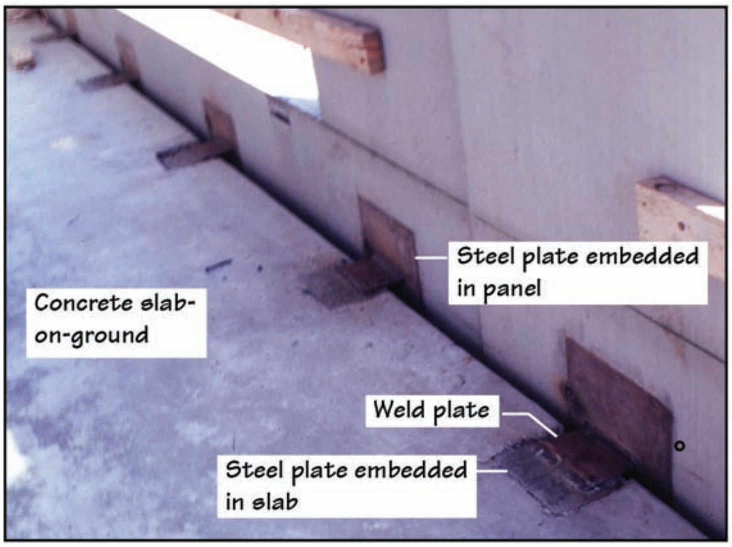
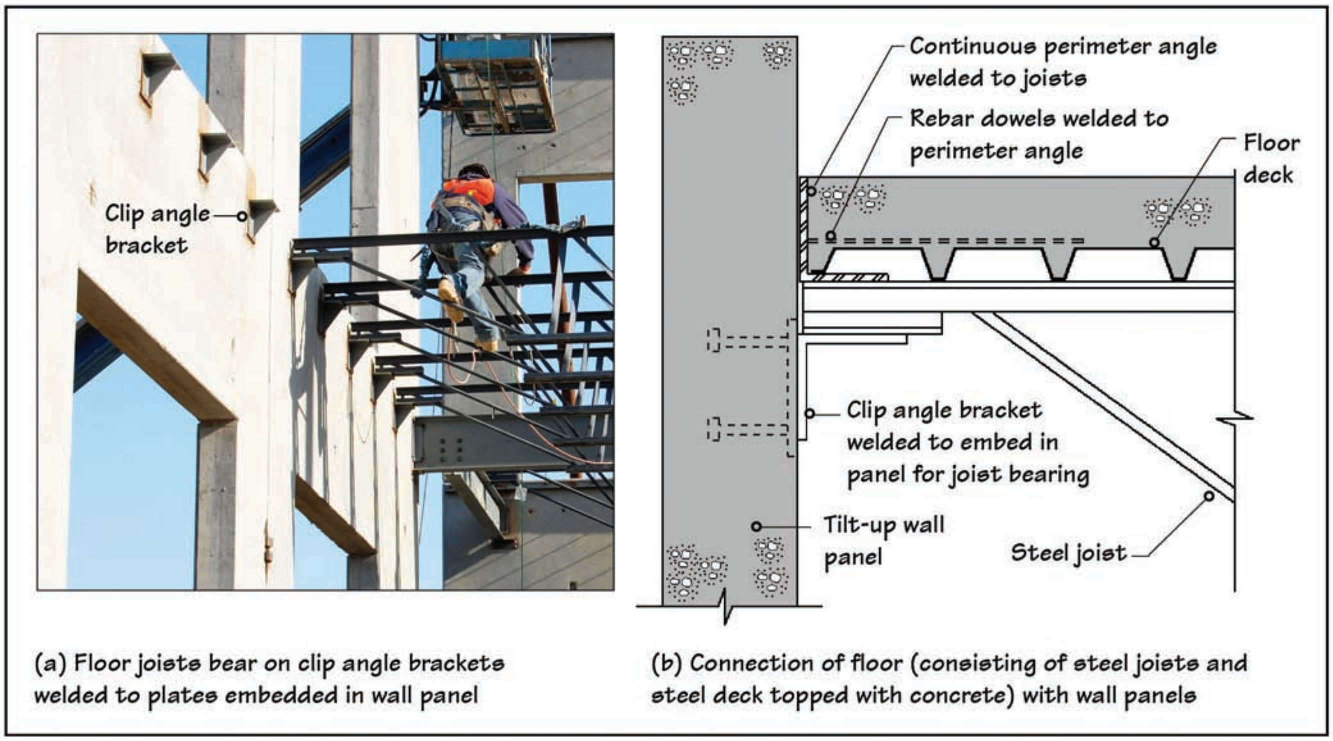


FIGURE 26.43 Detail of the connection between tilt-up wall panels and the concrete slab-on-ground using welded connections.

PANEL-TO-PANEL CONNECTION AND JOINT SEALS

The issue of connections between adjacent wall panels has been controversial. The earlier practice was to provide two or three welded connectors between all adjacent panels. The current practice is not provide any connection between panels so as to allow them to expand, contract, and deflect freely. Some architects and engineers would, however, provide the connection shown in Figure 26.47(a), which allows unrestrained in-plane movement of panels but restrains out-of-plane movement. This detail has the advantage in that the lateral (wind and seismic) loads are shared between adjacent panels.


Clip angle bracket
Continuous perimeter angle welded to joists
Rebar dowels welded to perimeter angle
Floor deck
Clip angle bracket welded to embed in panel for joist bearing
Tilt-up wall panel
Steel joist

(a) Floor joists bear on clip angle brackets welded to plates embedded in wall panel

(b) Connection of floor (consisting of steel joists and steel deck topped with concrete) with wall panels

FIGURE 26.44 Typical connection between a floor and tilt-up wall panels (see also Figure 26.46).

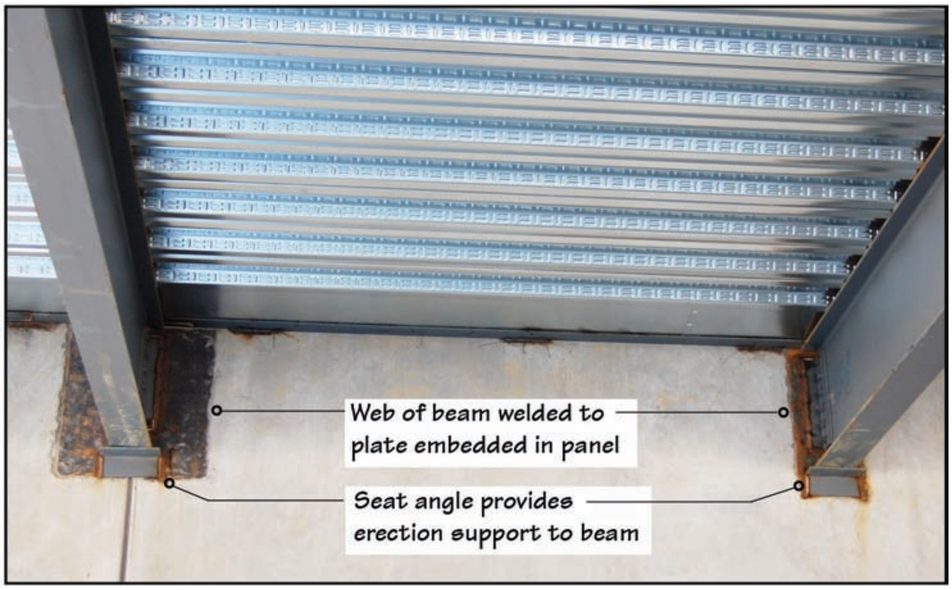

Web of beam welded to plate embedded in panel
Seat angle provides erection support to beam

FIGURE 26.45 Where wide-flange beams are used in place of steel joists to support the deck, they are welded through their webs to steel plates embedded in panels.

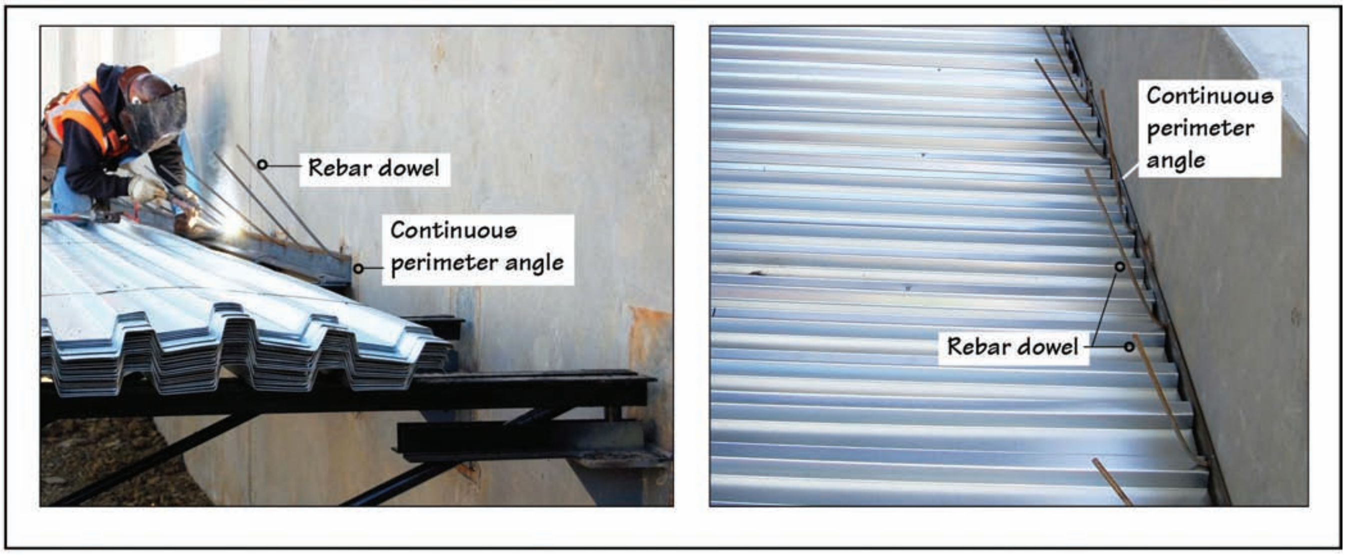

Rebar dowel
Continuous perimeter angle
Continuous perimeter angle
Rebar dowel

FIGURE 26.46 **(a)** A steel worker welds rebar dowels to a continuous perimeter angle with deck ribs parallel to perimeter angle. **(b)** Rebar dowels welded to perimeter angle perpendicular to deck ribs.

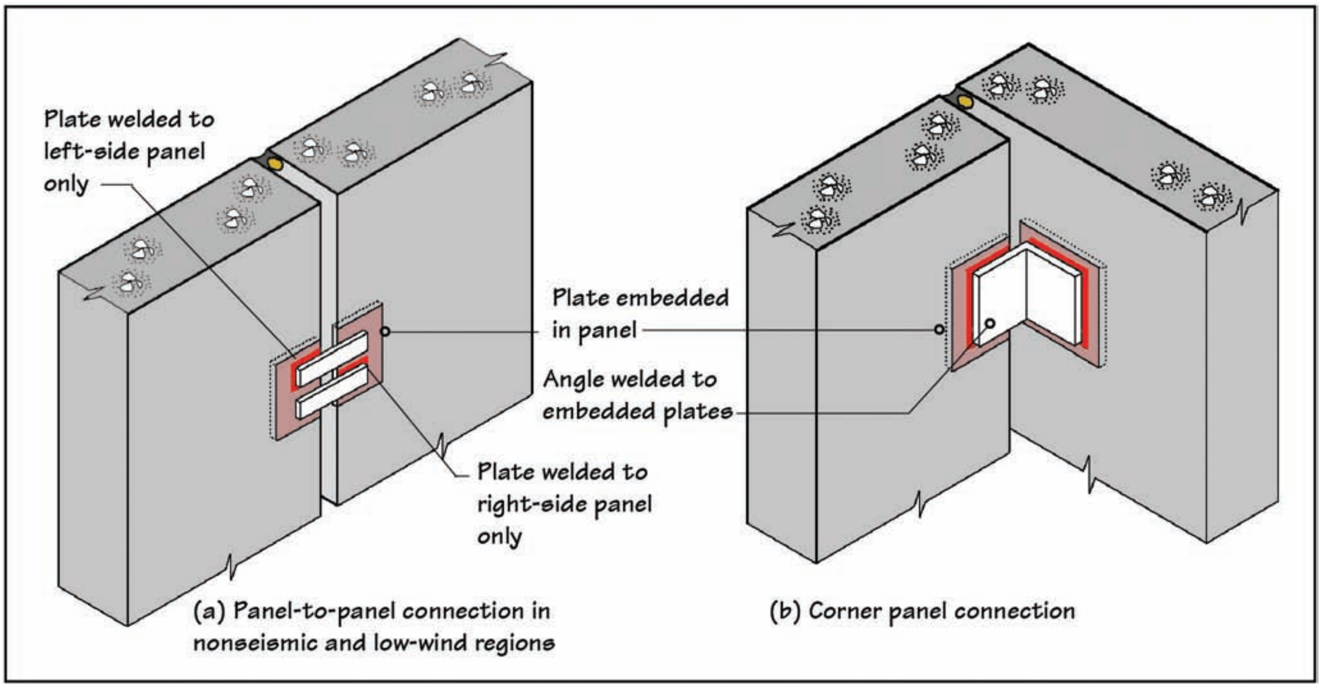


Plate welded to left-side panel only
Plate embedded in panel
Angle welded to embedded plates
Plate welded to right-side panel only
(a) Panel-to-panel connection in nonseismic and low-wind regions
(b) Corner panel connection

FIGURE 26.47 Details of connections between adjacent panels and between corner panels.

Welded connections between corner panels are recommended in all situations, Figure 26.47(b). The movement of panels at a corner is unique because the panels move in directions perpendicular to each other unlike the noncorner panels. Providing a welded connection between corner panels prevents a premature failure of the sealant between panels. Welded connections between adjacent noncorner panels in seismic and high-wind regions are also recommended.

While a single sealed joint between panels has been shown in Figure 26.47, a double sealed joint is preferable for greater air and water tightness. Both seals are applied from the outside, Figure 26.48. The outer seal includes weep holes.

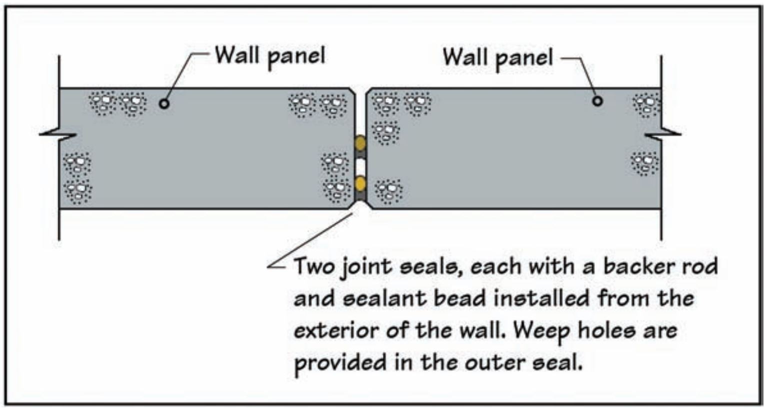

Wall panel
Wall panel
Two joint seals, each with a backer rod and sealant bead installed from the exterior of the wall. Weep holes are provided in the outer seal.

FIGURE 26.48 Double joint seal between panels.

26.11 EXTERIOR CLADDING AND INSULATION IN A TILT-UP WALL BUILDING

Tilt-up wall panels can be finished on the exterior in the same way as masonry walls. Cladding materials such as masonry veneer, Portland cement stucco, and EIFS may be used to clad the panels. However, because thick vertical concrete is water resistant, most tilt-up wall buildings are left unclad. Unclad tilt-up wall panels are typically painted, Figure 26.49. They may also be left in exposed concrete finish. Power washing and patching the panels is, however, required before painting them, Figure 26.50. Power washing removes the form-release agent and the dust collected on the panels during construction.

CONTINUOUS ENVELOPE INSULATION AND TILT-UP WALLS

Traditionally, the tilt-up wall buildings have been insulated from the inside with fiberglass insulation between cold-formed steel framing members, Figure 26.51. With continuous envelope insulation as the new requirement of the International Energy Conservation Code (IECC), this method of insulation is unacceptable because of the presence of thermal bridges at floor and roof levels from continuous perimeter angles and the concrete slab. To provide uninterrupted continuous insulation, two solutions are possible: (a) use EIFS cladding on the outside of panels (see Chapter 29) or (b) use sandwich tilt-up wall panels.

A sandwich tilt-up panel is similar to precast-concrete curtain wall panels (see Sections 28.6 and 28.7), and consists of two wythes of reinforced concrete separated by a layer of rigid plastic foam insulation. Because the panels are cast face down, the outer wythe, called the *face wythe*, is cast first followed by rigid insulation and then the backup wythe, Figure 26.52. The backup wythe is the structural wythe and contains the lifting inserts and other hardware.

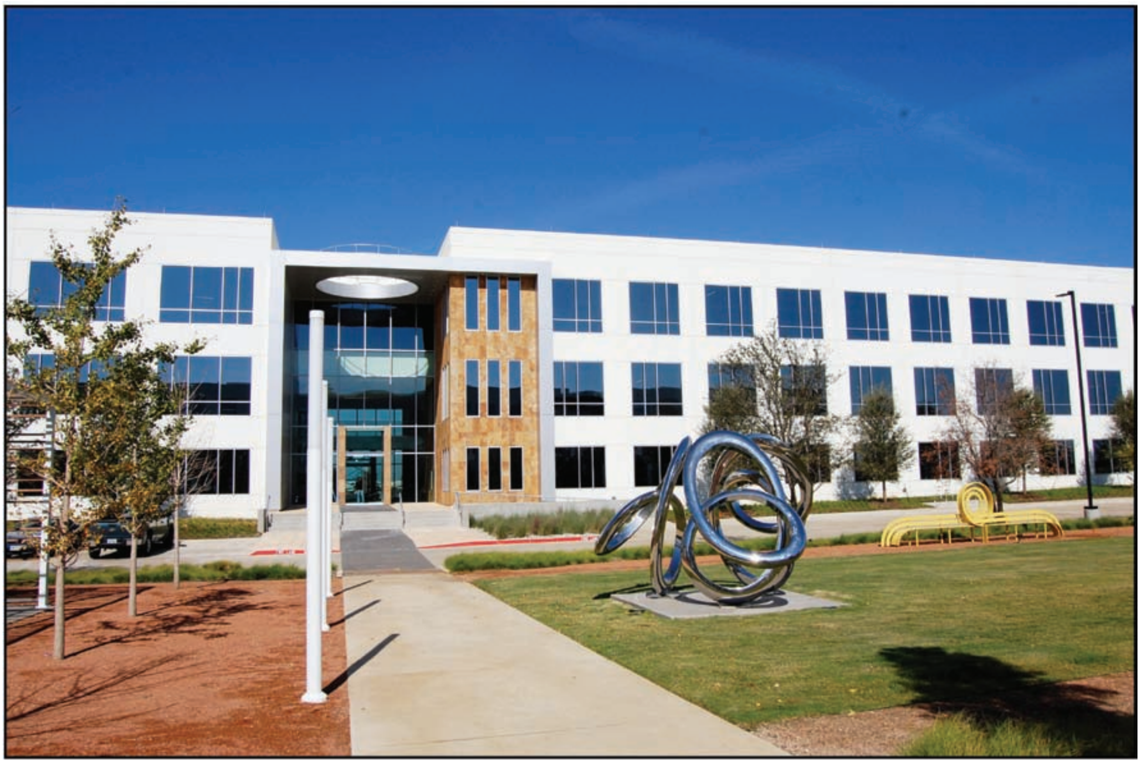


FIGURE 26.49 The exterior of most tilt-up wall buildings are simply paint finished, that is, they require no exterior cladding.

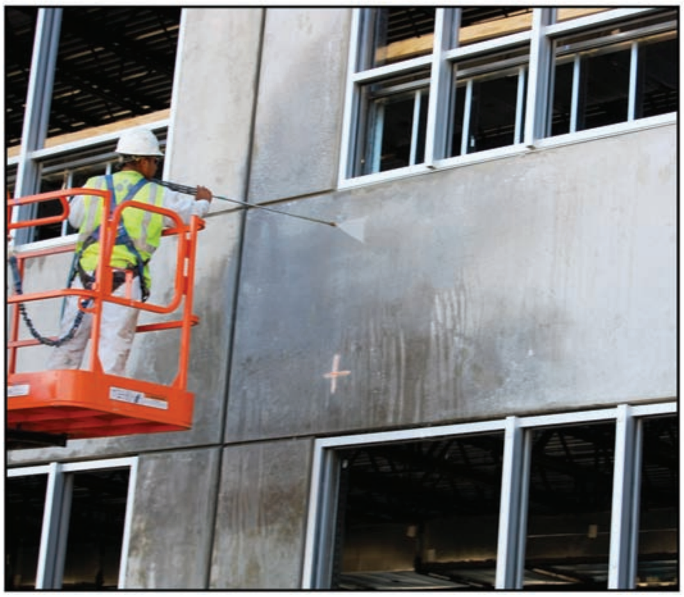


FIGURE 26.50 Power washing of tilt-up walls before painting them is required to remove construction dust and form-release agent.

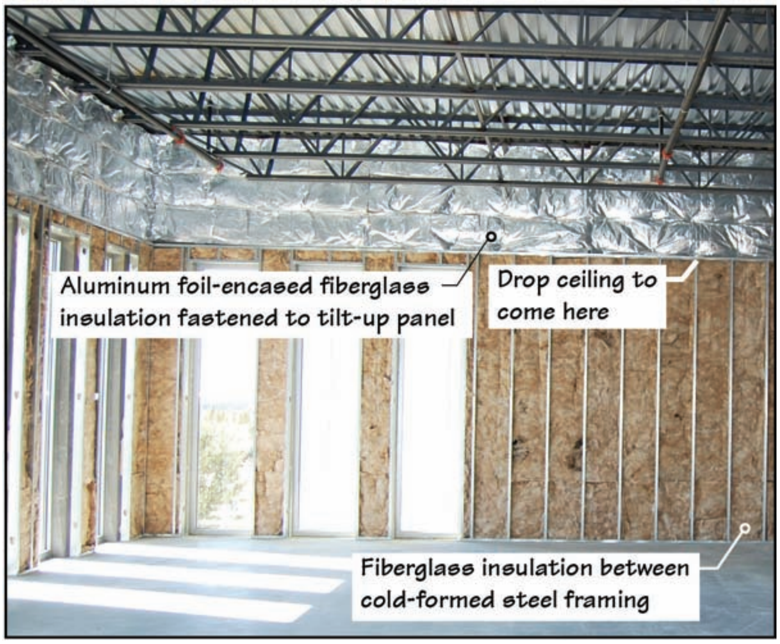

Aluminum foil-encased fiberglass insulation fastened to tilt-up panel
Drop ceiling to come here
Fiberglass insulation between cold-formed steel framing

FIGURE 26.51 Traditionally, a tilt-up wall building has been insulated on the inside with fiberglass insulation between cold-formed steel framing which is covered with gypsum board.

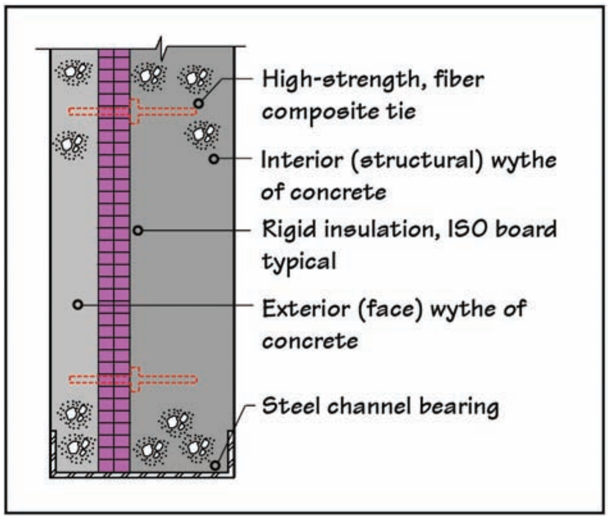

High-strength, fiber composite tie
Interior (structural) wythe of concrete
Rigid insulation, ISO board typical
Exterior (face) wythe of concrete
Steel channel bearing

FIGURE 26.52 Anatomy of a sandwich tilt-up wall panel.

The two concrete wythes and the insulation layer are tied together with ties made of high-strength fiber-composite material that has a higher R-value than the steel ties. The purpose of ties is simply to hang the face wythe on the structural wythe through the insulation, and thus allow the two concrete wythes to expand and contract independently.

Sandwich panels will be the new norm for tilt-up wall construction because of the increasing emphasis on energy conservation, which precludes (or reduces) the need for interior insulation and associated CFS framing. Additionally, if the concrete in face wythe is made with white Portland cement, exterior painting of tilt-up wall panels can be avoided. However, sandwich panels are thicker, require more concrete, greater lifting capacity of cranes, and greater quality control during panel casting because the pull-out strength of ties must be verified before casting the backup concrete wythe.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

22. The concrete tilt-up wall construction system is generally used in
- **a.** high-rise buildings—20 stories or more.
- **b.** mid-rise buildings—5 to 15 stories.
- **c.** low-rise buildings—1 to 4 stories.
- **d.** all of the above, depending on the local expertise and economy.

23. In a tilt-up wall construction system, the walls are
- **a.** cast in place at the construction site.
- **b.** precast in a plant and transported to the construction site for erection.
- **c.** precast at the construction site.
- **d.** (b) or (c), whichever is more economical.

24. The pipe braces that support concrete tilt-up walls are typically removed when
- **a.** all wall panels have been erected.
- **b.** all walls panels have been erected and anchored to the footings.
- **c.** all wall panels have been erected, anchored to the footings, and the floor structures have been completed.
- **d.** all wall panels have been erected, anchored to the footings, and the floor and roof structures have been completed.
- **e.** all wall panels have been erected, anchored to the footings, the floor and roof structures have been completed, and the exterior finish to wall panels has been applied.

25. The most commonly used strength of concrete for tilt-up wall panels is
- **a.** 6,000 psi.
- **b.** 5,000 psi.
- **c.** 4,000 psi.
- **d.** 3,000 psi.
- **e.** 2,000 psi.

26. The most commonly used strength of concrete for the slab-on-ground in concrete tilt-up wall buildings is
- **a.** 6,000 psi.
- **b.** 5,000 psi.
- **c.** 4,000 psi.
- **d.** 3,000 psi.
- **e.** 2,000 psi.

27. The foundations for concrete tilt-up walls consist of
- **a.** continuous strip footings.
- **b.** isolated pad footings.
- **c.** drilled pier footings.
- **d.** any one of the above.
- **e.** none of the above.

28. During the erection of concrete tilt-up wall panels, a gap is left between the bottom of a panel and the top of the footing. This gap is approximately
- **a.** $\frac{1}{2}$ in. to 1 in.
- **b.** 1 in. to 2 in.
- **c.** 2 in. to 3 in.
- **d.** none of the above.

29. The most commonly used method of connecting tilt-up walls to the slab-on-ground is
- **a.** a continuous steel angle welded to panels and the slab-on-ground.
- **b.** a continuous concrete closure strip in the slab-on-ground.
- **c.** individual steel plates welded to panels and the slab-on-ground.
- **d.** (a) or (c).
- **e.** (b) or (c).

30. The adjacent noncorner tilt-up wall panels
- **a.** are connected using a continuous steel plate extending from the bottom of the panel to its top.
- **b.** are connected using 6 in. × 6 in. steel plates at 6 ft on center.
- **c.** should not be connected unless the building is located in a seismic region.
- **d.** should not be connected unless the building is located in a seismic or high-wind region.

(*Continued*)

31. The adjacent corner tilt-up wall panels should be connected together in all situations.

- **a.** True
- **b.** False

32. Reinforced-concrete tilt-up walls are generally used as

- **a.** load-bearing enclosure walls whereas the interior structure consists of a structural steel frame.
- **b.** non-load-bearing enclosure walls whereas the entire structure consists of a structural steel frame.
- **c.** load-bearing enclosure walls whereas the interior structure consists of a cast-in-place reinforced-concrete frame.
- **d.** load-bearing enclosure walls whereas the interior structure consists of a precast-concrete frame.
- **e.** any one of the above.

33. To provide continuous insulation in a tilt-up wall building, the choice generally is the use of

- **a.** EIFS cladding on wall panels.
- **b.** sandwich tilt-up wall panels.
- **c.** masonry veneer cladding with rigid insulation between panels and cladding.
- **d.** (a) or (b).
- **e.** (b) or (c).

34. In a sandwich tilt-up wall panel, the structural wythe of concrete is on the exterior face of the wall.

- **a.** True
- **b.** False

35. The most commonly used exterior finish on tilt-up wall panels is

- **a.** Portland cement stucco.
- **b.** EIFS.
- **c.** anchored masonry veneer.
- **d.** adhered masonry veneer.
- **e.** paint.

REVIEW QUESTIONS

1. With the help of sketches and notes, explain why the walls in a traditional masonry bearing wall structure had to be extremely thick.
2. Explain the importance of vertical reinforcement in load-bearing masonry walls.
3. With the help of sketches and notes, explain why it is desirable to reinforce the ends, corners, and jambs around openings in the walls of load-bearing masonry buildings.
4. What is the purpose of bond beams, and where are they required in a typical load-bearing masonry structure?
5. List the various load-bearing wall systems described in this chapter.
6. With the help of a sketch, explain what the tunnel form is, and its benefits and limitations.
7. Explain why the live load on the slab-on-ground in a concrete tilt-up wall building is generally higher during the construction of the building than in-service live load.
8. With the help of a sketch and notes, explain what a closure strip is with respect to a tilt-up wall building.
9. Explain why tilt-up wall panel-to-panel connections are discouraged and why they are necessary for corner panels. In which situations, panel-to-panel connections are required?
10. With the help of sketches and notes, explain the details of
    - a. Double-sealed tilt-up wall panels
    - b. Tilt-up wall sandwich panels

CHAPTER 27

Exterior Wall Cladding–I (Principles of Rainwater Infiltration Control)

CHAPTER OUTLINE

27.1 RAINWATER INFILTRATION CONTROL—GENERAL PRINCIPLES

27.2 RAINWATER INFILTRATION CONTROL AND EXTERIOR WALLS

27.3 RAIN-SCREEN EXTERIOR CLADDING

27.4 CONTINUOUS INSULATION AND EXTERIOR CLADDING

Exterior walls are one of the major determinants of the appearance of a building. They convey images such as strength or solidity (brick- or stone-clad walls), lightness or openness (glass-metal curtain walls), or a sense of movement or activity (bright, glistening metal curtain walls). In terms of the building's performance, the importance of exterior walls is even greater. Together with the roof, they constitute the building's envelope, providing the separation between inside and outside and serving to maintain an acceptable interior environment.

The exterior walls can serve the envelope function only if they are able to perform well under a range of environmental conditions. They must:

a. Prevent water infiltration from rain and snow.
b. Control heat loss and heat gain.
c. Control air leakage and water vapor transmission.
d. Resist fire.
e. Control sound transmission.
f. Accommodate movement due to thermal, moisture, and other causes.

Factors (b) to (f) are covered in Chapters 5–9. Water infiltration is, however, the most critical of all concerns. Its importance is universal because no building can be considered a shelter unless its envelope is water resistant. Additionally, a water-resistant envelope has been the fundamental requirement of buildings throughout the ages—well before other environmental factors emerged as design concerns.

This chapter focuses on the principles of water infiltration control in exterior wall assemblies. The construction and detailing of a variety of these assemblies is covered in Chapters 28 (Exterior Wall Cladding-II), 29 (Exterior Wall Cladding-III), and 32 (Exterior Wall Cladding-IV). The principles of water infiltration control in basement walls are covered in Chapter 12, and roofs are discussed in Chapters 33 and 34.

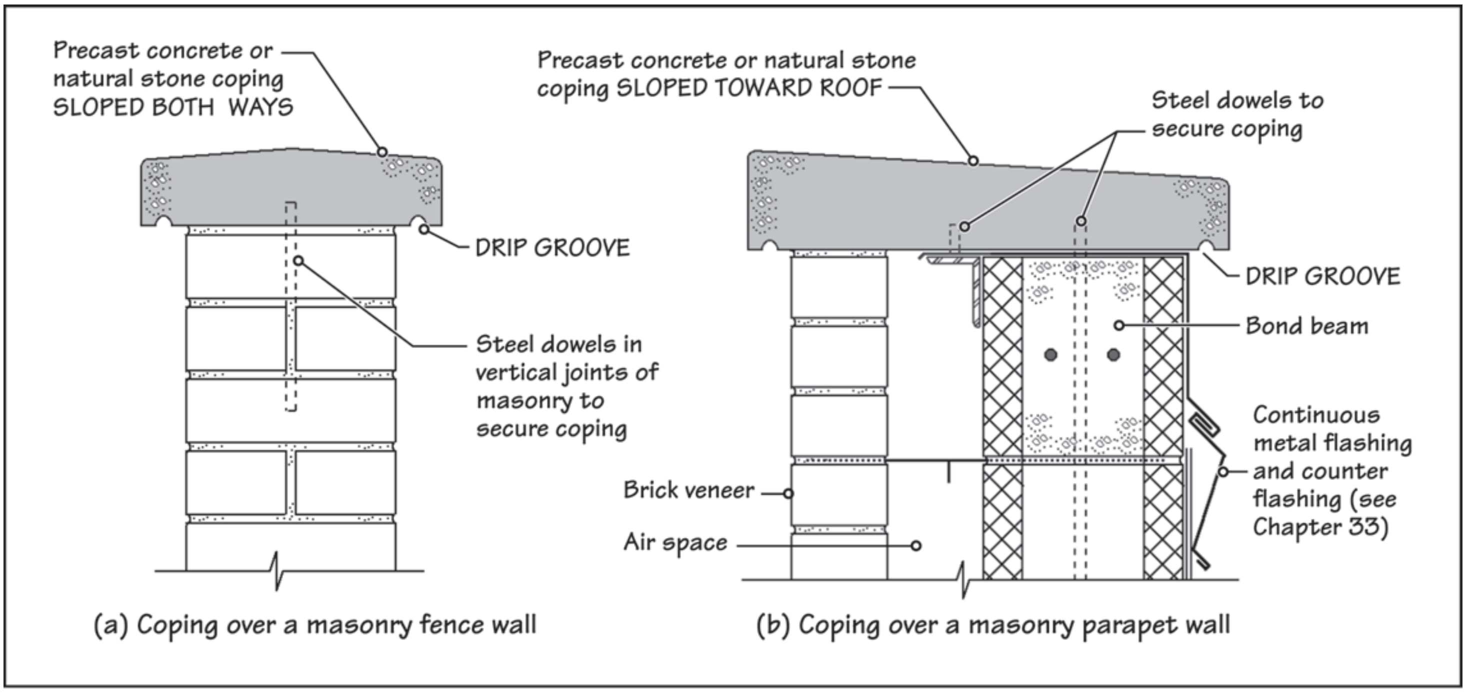

Precast concrete or natural stone coping SLOPED BOTH WAYS
DRIP GROOVE
Steel dowels in vertical joints of masonry to secure coping
(a) Coping over a masonry fence wall
Precast concrete or natural stone coping SLOPED TOWARD ROOF
Steel dowels to secure coping
DRIP GROOVE
Bond beam
Continuous metal flashing and counter flashing (see Chapter 33)
Brick veneer
Air space
(b) Coping over a masonry parapet wall

FIGURE 27.1 The importance of sloping the exposed horizontal surfaces of a wall.

27.1 RAINWATER INFILTRATION CONTROL—GENERAL PRINCIPLES

Three major forces that affect water infiltration through exterior walls are gravity, the capillary effect, and wind. Because these forces frequently act on an assembly simultaneously, multiple strategies must be used in the same assembly to counter water infiltration.

GRAVITY-INDUCED INFILTRATION

Gravity generally affects water penetration through an exposed horizontal surface of a wall and can be countered by providing a nominal slope in the surface. The purpose of slope (usually 1:12) is to drain water away from vulnerable parts of a building. Thus, a roof overhang protects the upper portion of a wall, and the coping on the top of a masonry fence wall is sloped on both sides of the wall, Figure 27.1.

The coping over a roof parapet is generally sloped toward the roof so that the water drains on the roof. In exterior window sills and thresholds under entrance doors, the slope is directed away from the building.

CAPILLARY-INDUCED INFILTRATION

Water molecules are subjected to forces of attraction between them, creating an intermolecular cohesive bond between them. In addition to the cohesive bond, water molecules experience forces of attraction from the molecules of the surface with which they are in contact. These forces create an adhesive bond. For most building surfaces, the adhesive bond is stronger than the cohesive bond. It is because of the stronger adhesive bond that a thin film of water is able to travel horizontally along the soffit instead of dropping vertically by gravity. A drip mechanism, which consists of either a continuous groove or a vertical projection, counteracts this phenomenon, as shown in Figures 27.1 and 27.2.

Cohesive and adhesive forces also create the capillary effect, which is responsible for suction forces that occur in tiny spaces between two surfaces (surfaces in very close proximity to each other). In this case, the water is sucked between the surfaces.

Water can also be sucked into the tiny pores of porous materials such as brick, CMU, or stone. Coating the surface of a porous material with a sealer helps close the pores. Because the sealer degrades rapidly due to ultraviolet radiation, abrasion, and other physical processes, the use of sealers is not a durable means of waterproofing a porous surface. To be effective, seals on exterior walls need frequent reapplication.

Capillary suction can also occur in a joint between two nonporous materials if the joint is narrow. In narrow joints, capillary suction can be prevented by introducing a larger space,

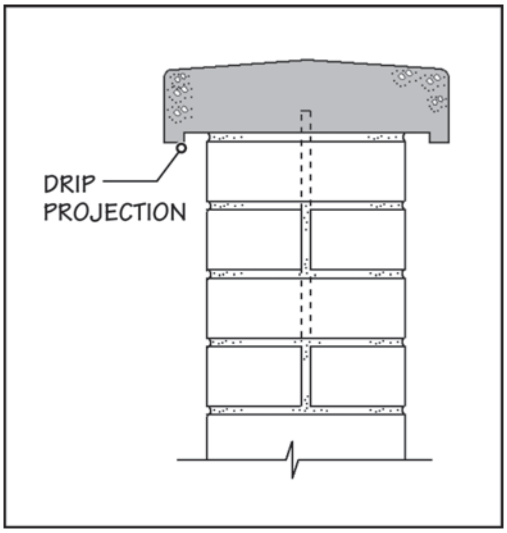


FIGURE 27.2 Detail of Figure 27.1 (a) redrawn with a drip projection in the coping instead of a drip groove.

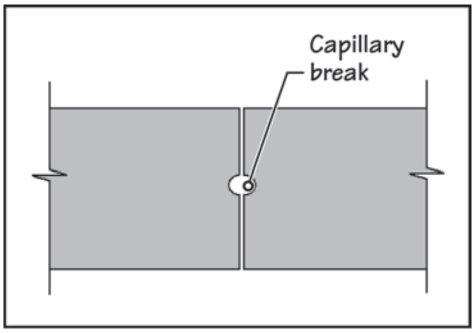


FIGURE 27.3 A narrow space can be made more water resistant by providing a capillary break.

nearly $\frac{1}{4}$ in. or wider, immediately beyond the capillary space. This space is referred to as the *capillary break*, Figure 27.3.

WIND-INDUCED INFILTRATION

Providing an *overlap* between members meeting at a joint is another commonsense measure. The force of wind can impart kinetic energy to water, causing the water to travel horizontally as well as vertically in the joint. Therefore, the overlap must be sufficiently large to present a reliable baffle against wind-driven rain, Figure 27.4. A lapped horizontal joint performs better than a lapped vertical joint, because water has to work against the force of gravity to get across the overlap in a horizontal joint. Capillary breaks can also be included in a lapped joint.

A horizontal butt joint can be made infiltration resistant by incorporating L- or Z-flashing, Figure 27.5. L- or Z-flashing consists of an impervious membrane that provides a barrier to water and directs it to the exterior surface. Various types of sheet materials—galvanized steel, stainless steel, copper, lead, and polyvinyl chloride (PVC)—are used as flashing materials. Other uses of flashing are shown in Figures 27.6 and 27.8.

THE IMPORTANCE OF JOINT SEALANTS

Filling joints with sealants (see Chapter 9) is another commonly used strategy to keep water from penetrating through joints between building components. Because sealants degrade

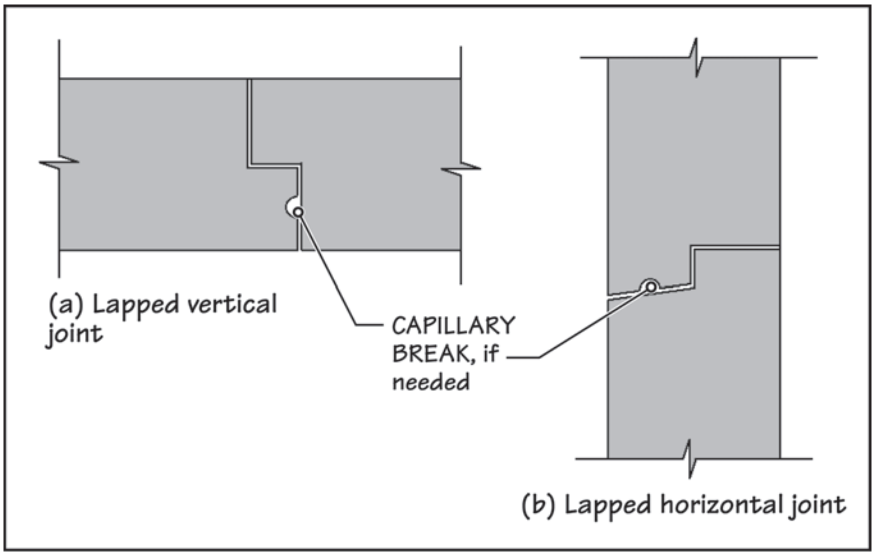


FIGURE 27.4 Lapped vertical and horizontal joints.

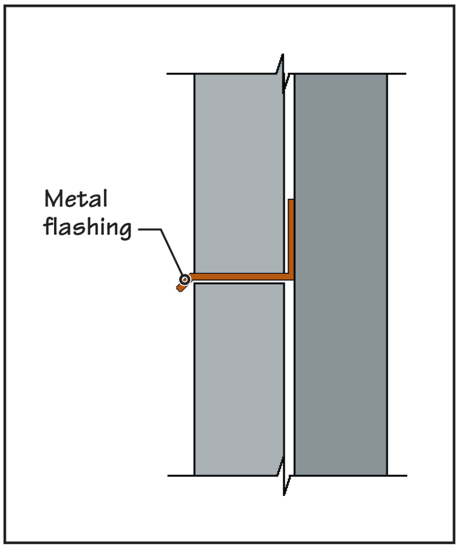


FIGURE 27.5 L-flashing at a horizontal butt joint. If the projecting part of flashing is turned down at a 90° angle instead of a 45° angle, it is referred to as Z-flashing.

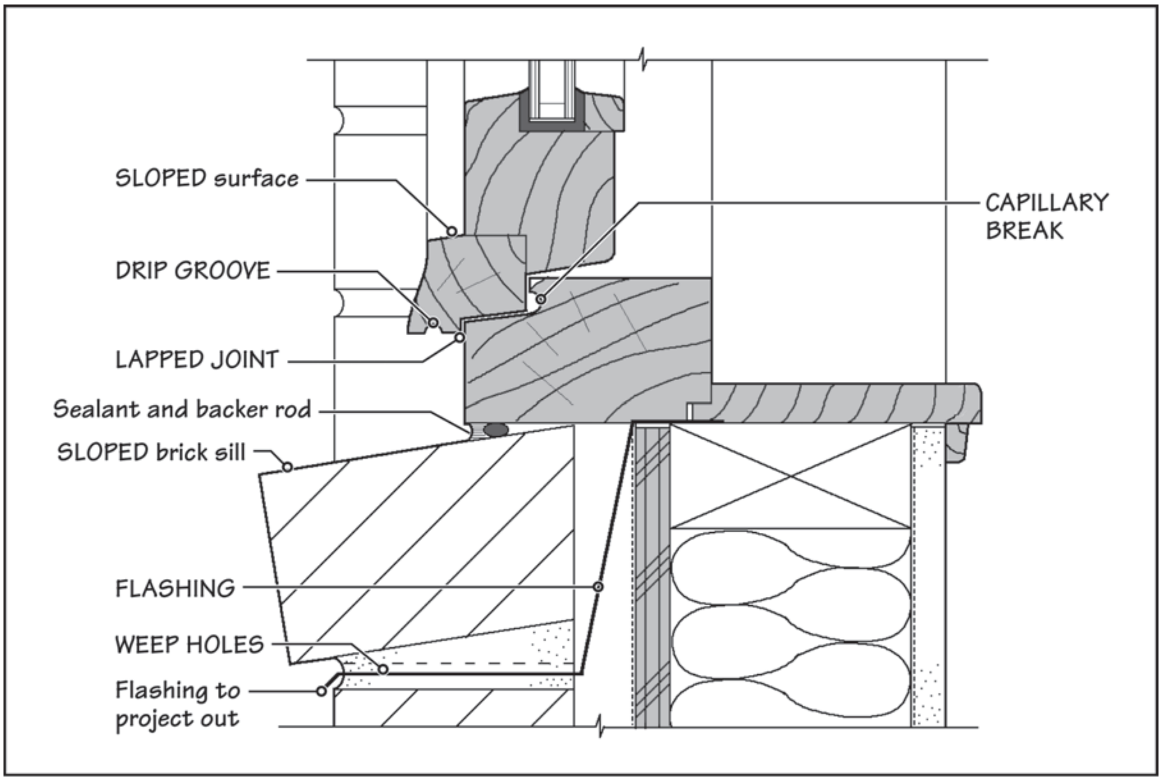


FIGURE 27.6 A section at a window sill showing various rainwater leakage control strategies used in one detail.

over time from exposure to environmental factors, particularly solar radiation and water, they should not be relied upon as the only water-resisting element. A certain amount of redundancy must be built into the detail in case the sealant fails. Usually all or most of the strategies previously discussed are used in a single detail, as shown in a section at the sill level of a typical wood window, Figure 27.6.

27.2 RAINWATER INFILTRATION CONTROL AND EXTERIOR WALLS

Water-resistant exterior walls may be divided into three types:

- Walls with overhangs
- Barrier walls
- Drainage walls

WALLS WITH OVERHANGS

This type of wall system depends on protective floor and roof overhangs to prevent water infiltration, Figure 27.7. It has limited application because the overhangs are required to shield the wall completely from wind-driven rain and, therefore, must be quite deep. In addition, the overhangs impose economic as well as design constraints on the exterior envelope, particularly that of a multistory building. However, a shallow roof overhang is commonly used in a low-rise building (eave projection) and can provide substantial protection from water penetration at the wall-roof junction.

BARRIER WALLS—FACE-SEALED WALLS AND RESERVOIR WALLS

A barrier wall is a wall that functions as the primary structure and, at the same time, performs as the building envelope. Historic buildings such as the Monadnock Building (see Chapter 26) and some contemporary CMU load-bearing structures are examples of this wall type. This wall type resists water infiltration either: (a) by providing an impervious barrier to water, referred to as a *face-sealed wall*, or (b) by functioning as a water reservoir—a *reservoir wall*.

An example of a face-sealed wall is a CMU or concrete wall system with an applied water-resistant veneer, such as EIFS or stucco (see Chapter 29). On the other hand, an

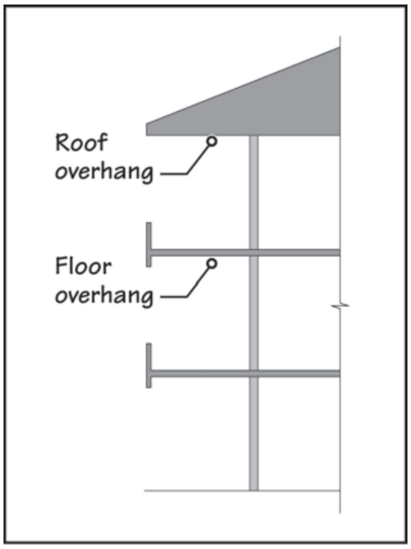


FIGURE 27.7 Deep roof and floor overhangs can substantially reduce water leakage from wind-driven rain through walls.

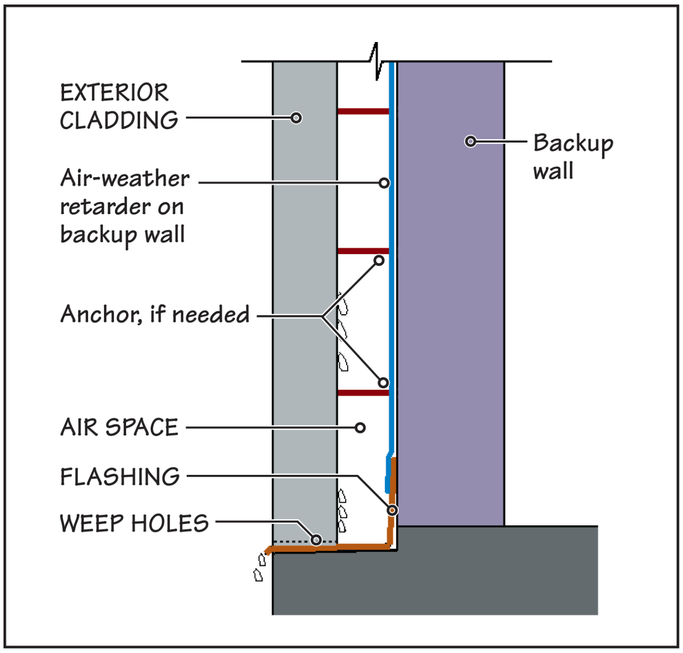


FIGURE 27.8 A section through a drainage wall showing its important water infiltration control features. (Note that the air space in a drainage wall may also have insulation, which is not part of water infiltration control.)

example of a barrier wall that acts as a reservoir is a porous masonry or concrete wall that is so thick that any absorbed water is unable to migrate to the wall's interior surface. The thicker the wall, the larger the reservoir. In this type of wall, only the outer layer of the wall gets wet, even during a long rainy spell; given a long dry spell, the entire wall will dry again.

It is very important that a barrier wall does not develop through-wall cracks that may be caused by weathering, expansion or contraction, foundation settlement, and so on. If cracks develop, water infiltration will result. Careful detailing and attention to water resistance in materials are, therefore, essential to the long-term performance of a barrier wall.

DRAINAGE WALL

A relatively more water-resistant exterior wall is a drainage wall. It is a wall that consists of an exterior cladding, an inner backup wall, and an intervening air space between the cladding and the backup.

In a drainage wall, the exterior cladding is the first defense against water infiltration. Therefore, it is made as water resistant as possible. However, some water will inevitably penetrate through the cladding. Any water that leaks through the cladding collects in the air space and is drained out through small openings at the bottom of the cladding called *weep holes*, Figure 27.8.

IMPORTANT FEATURES OF A DRAINAGE WALL

A drainage wall must have sufficient built-in redundancy to remain infiltration-free for the entire life of the building and includes the following features:

- Exterior cladding
- Air space
- Flashing
- Water-resistant backup
- Weep holes

Flashing in a drainage wall is a continuous waterproof membrane providing a continuous barrier that originates at the backup wall and penetrates through the air space and cladding. The purpose of flashing is to collect and channel any water that gets into the air space back to the exterior. It is attached to the backup wall at the bottom of a section of a drainage wall and works in conjunction with weep holes, which allow water to escape.

The *water-resistant layer* on the backup wall protects it from water that may accidentally reach the backup wall by traveling over metal anchors (where used) or unintentional obstructions in the air space. It also functions as an air barrier (retarder). Thus, this layer is an air-weather retarder. Because the water-resistant layer is shielded by the cladding, it does not degrade as rapidly as an exposed surface.

Although the drainage wall concept was initially introduced with reference to a porous exterior cladding consisting of brick, CMU, concrete, or stone, it applies equally to an impervious exterior cladding, such as one of glass or metal. Note that the underlying philosophy of the drainage wall is the redundancy of its two water-resistant layers. If the exterior layer is made of an impervious material, the redundancy is that much greater.

EXPAND YOUR KNOWLEDGE

Exterior-Wall Cladding Systems: Curtain Wall, Veneer Wall, and Infill Wall

The primary exterior-wall types in use today are curtain walls, veneer walls, and infill walls.

Curtain Walls

As the name suggests, a *curtain wall* forms a curtain on the exterior face of a building. It is used with a frame structure, covers the building's structural frame, and is directly suspended from it. In a curtain wall, the wind loads are transferred directly from the curtain wall to the building's structural frame.

A 2-in. minimum separation is generally required between the curtain wall and the building's structural frame to accommodate unintended dimensional irregularities in the frame.

A typical example of a curtain wall is a *glass-aluminum curtain wall* (see Chapter 32). *Opaque curtain walls* consist of precast concrete panels, glass fiber–reinforced panels, metal panels, and so on. A backup wall may be used in an opaque curtain wall to provide an interior wall finish and to incorporate insulation, electrical, and other utility conduits within the wall. Because the wind load is resisted by the curtain wall, the backup wall in this assembly (if provided) does not experience any wind loads.

Veneer Walls

Another exterior-wall cladding that is similar to an opaque curtain wall is a *veneer wall*. A veneer wall can be used with both a frame structure and a bearing wall structure. A backup wall is always required in a veneer wall. The wind loads that act on the veneer wall are transferred to the backup wall. The backup wall then transfers them to the building's structural frame. A veneer wall may be of two types:

- Anchored veneer
- Adhered veneer

In an *anchored veneer*, the anchors connect the veneer to the backup; therefore, they participate in transferring the wind loads from the veneer to the backup wall. An anchored veneer wall is typically designed as a drainage wall with a minimum 2-in. air space between the veneer and the backup wall.

A veneer may also be applied without anchors, in which case it is adhered to the backup wall. Such a veneer is called an *adhered veneer*. An adhered veneer wall is a face-sealed (barrier) wall, unlike the anchored veneer. Stucco and EIFS wall assemblies are examples of face-sealed barrier walls.

Infill Walls

Like a curtain wall and a veneer wall, an infill exterior wall is a non-load-bearing wall assembly. It occupies the space between the building's columns and beams, leaving the structural frame exposed to the outside. An infill wall can be used only with a frame structure. It can be designed as either an anchored infill wall or an adhered infill wall.

Before energy-use concerns became critical, most exterior-wall assemblies were designed as infill walls, Figure 1. In these buildings, the steel or concrete structural frame, having an extremely low R-value, contributed to substantial thermal short-circuiting. In contemporary buildings, the use of curtain walls or veneer walls is the norm because they cover the building's structural frame and, therefore, can be designed with greater thermal efficiency.

Exterior Cladding

The term *exterior-wall cladding* (or simply *cladding*) is a general term that is used for all exterior wall finishes.

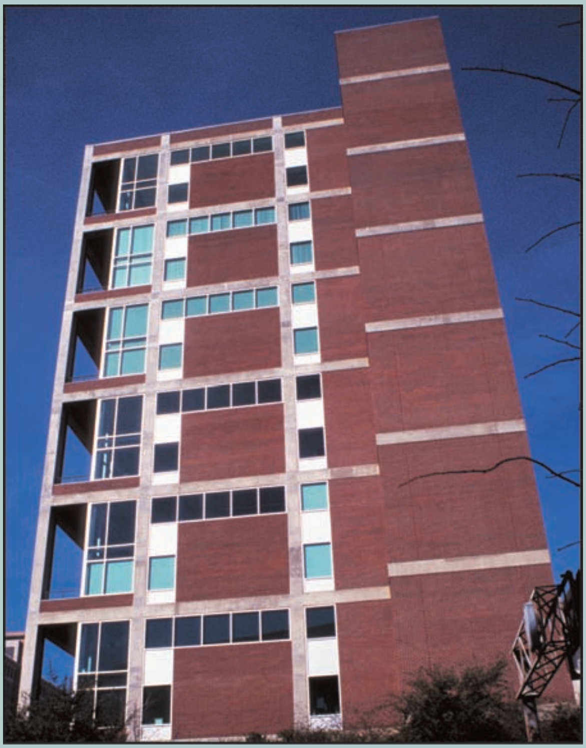
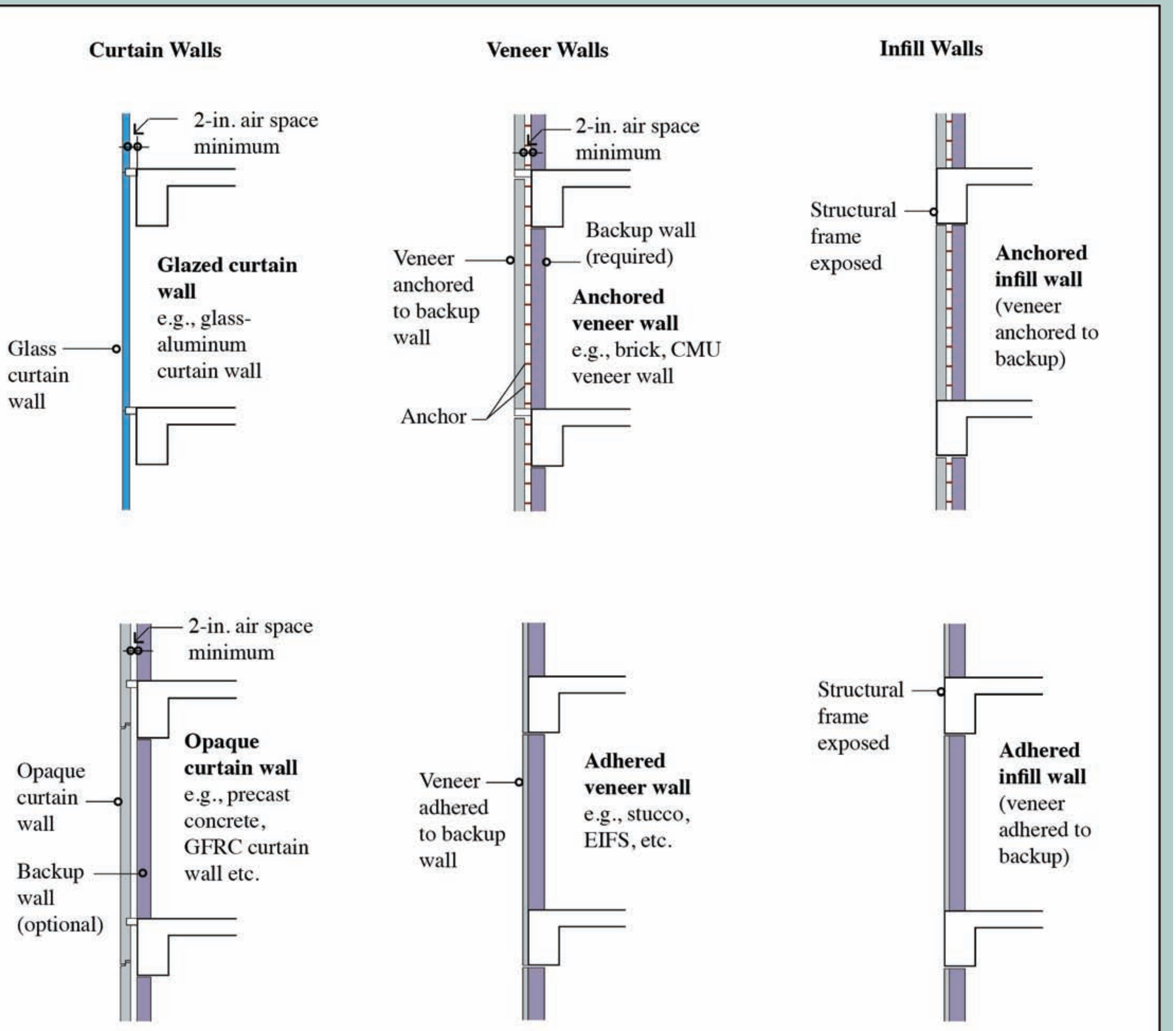


FIGURE 1 A typical example of an exposed structural frame and exterior infill walls.



Curtain Walls
Veneer Walls
Infill Walls
2-in. air space minimum
Glazed curtain wall
e.g., glass-aluminum curtain wall
Glass curtain wall
2-in. air space minimum
Backup wall (required)
Veneer anchored to backup wall
Anchored veneer wall
e.g., brick, CMU veneer wall
Anchor
Structural frame exposed
Anchored infill wall
(veneer anchored to backup)
2-in. air space minimum
Opaque curtain wall
e.g., precast concrete, GFRC curtain wall etc.
Opaque curtain wall
Backup wall (optional)
Adhered veneer wall
e.g., stucco, EIFS, etc.
Veneer adhered to backup wall
Structural frame exposed
Adhered infill wall
(veneer adhered to backup)

- A curtain wall is used only with a frame structure.
- Wind loads on a curtain wall are transferred directly to building's structural frame. A backup wall (when used with an opaque curtain wall) does not experience wind loads.

- A veneer wall can be used with a frame structure or a bearing wall structure.
- A backup wall is required in a veneer wall assembly.
- Wind loads are transferred from the veneer to the backup wall, which in turn, transfers the wind loads to the building's structure.

- An infill wall is used only with a frame structure.
- An infill wall may consist of a cavity drainage wall or a single (barrier) wall.
- Wind loads are transferred from the infill wall to the building's structural frame.

FIGURE 2 Curtain wall, veneer wall, and infill wall defined.

27.3 RAIN-SCREEN EXTERIOR CLADDING

A rain-screen cladding system includes the basic principles of the drainage wall system, but it also addresses the issue of water penetration due to unequal distribution of air pressure on the exterior of the wall and in the air space between the cladding and the backup wall. The equalization of pressure is required when gaps and breaches in exterior cladding (such as weep holes, cracks, and apertures between masonry units and mortar joints) become sources of water penetration by suction under conditions of wind-driven rain.

In order to reduce the suction of water in a drainage wall, the pressure between the air space and the outside should be equalized as much as possible. Pressure equalization is accomplished by not completely sealing the cladding. In fact, providing weep holes and purposely incorporating other openings in the cladding help to create pressure equalization.

If the openings in the cladding of a drainage wall, such as weep holes, are few and small in area, the pressure between the air space and the exterior cladding will not be equalized. In such a wall, although the air space is under atmospheric pressure, the outside surface of the cladding is subjected to a pressure greater than the atmospheric pressure. This will cause the water to be sucked into the air space through the weep holes. Water will also be sucked into the air space through joints in cladding that are inadequately sealed or have become leaky over time.

Water suction will take place on the windward facade only because at this facade, the pressure in the air space is lower than the outside pressure. On the other facades, the air space pressure is higher than the outside pressure. Hence, no suction takes place through nonwindward facades.

EXPAND YOUR KNOWLEDGE

Rain-Screen and Pressure Equalization

To fully appreciate the phenomenon of the suction of water into the air space in a drainage wall, the fundamentals of wind loads on buildings must be reviewed. When there is no wind (zero wind speed), the air pressure on the inside and outside surfaces of the walls of an enclosure is the same, equal to the atmospheric pressure—2,100 psf. Because atmospheric pressure works on both sides of a wall equally, the wall is under perfect equilibrium, and there is no wind load on the wall, Figure 1.

Equilibrium is disturbed by wind, which creates additional pressure on the outside surface of a windward wall, whereas the pressure in the enclosure is equal to the atmospheric pressure. For example, if the wind speed is 100 mph, the wind load on the wall is nearly 25 psf (see Section 3.5). This means that the outside surface of the windward wall is under a pressure of 2,125 psf, but the enclosure is under a pressure of 2,100 psf, Figure 2.

It is this difference between the inside and outside air pressures that we refer to as the *wind load* (see Section 3.5). It is also this pressure difference that causes suction of water through the windward cladding because the pressure in the (drainage) air space is atmospheric pressure, whereas the pressure on the exterior face of cladding is greater than the atmospheric pressure.

If the windward wall has large openings and the rest of the enclosure has no openings at all, the wind will move into the enclosure and the air pressure inside the enclosure will be equal to the outside pressure, as shown in Figure 3. In the case of perfect equalization of pressures, the windward wall will not be subjected to any wind load, and no suction will be created at the windward wall.

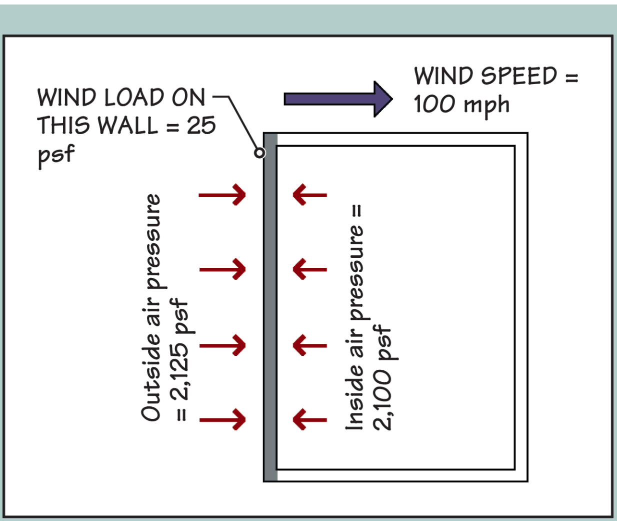

WIND LOAD ON THIS WALL = 25 psf
WIND SPEED = 100 mph
Outside air pressure = 2,125 psf
Inside air pressure = 2,100 psf

FIGURE 2 Outside and inside air pressures on a windward wall of a fully enclosed building.

Atmospheric Pressure Equalization and Human Bodies

Atmospheric air pressure is due to the weight of a column of air on the Earth's surface. This equals the pressure that a 29.92-in. (say, 30 in. = 2.5 ft) column of mercury exerts at the column's bottom. It equals 14.7 psi, or approximately 2,100 psf.

A pressure of 2,100 psf is the same pressure that a 14-ft-thick concrete slab will exert at its base. In other words, human bodies are subjected to the same pressure that is exerted by a 14-ft-thick concrete slab at its base. We are not squashed by this pressure (i.e., there is no wind load on our bodies) because the interior of our bodies also contains air, and there is air pressure equalization between the inside and outside of our bodies. (Because concrete weighs about 150 pounds per cubic foot [pcf], a 14-ft-high concrete column exerts a pressure of about 2,100 psf at its base. Mercury weighs approximately 850 pcf. Therefore, only a [30-in.] 2.5-ft-high mercury column exerts the same pressure.)

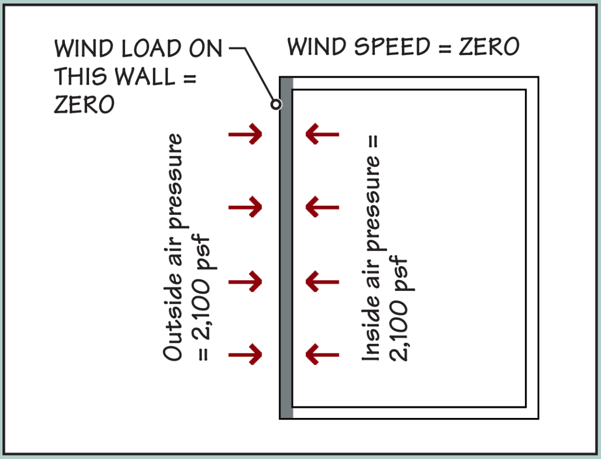

WIND LOAD ON THIS WALL = ZERO
WIND SPEED = ZERO
Outside air pressure = 2,100 psf
Inside air pressure = 2,100 psf

FIGURE 1 Outside and inside air pressures on a wall under zero wind speed.

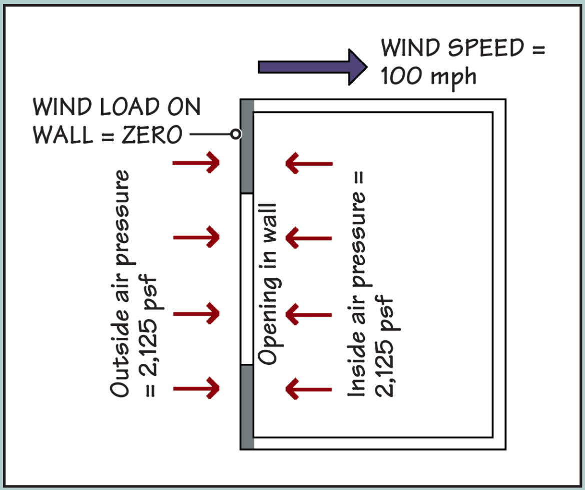

WIND SPEED = 100 mph
WIND LOAD ON WALL = ZERO
Outside air pressure = 2,125 psf
Opening in wall
Inside air pressure = 2,125 psf

FIGURE 3 Outside and inside air pressures in an enclosure that has a large opening on the windward wall.

WIND LOAD ON THE CLADDING OF A PRESSURE-EQUALIZED WALL

Because there is no pressure differential between the inside and outside faces of cladding in a pressure-equalized drainage wall, the cladding is not subjected to any wind load. In such a wall, all of the wind load acts on the backup, and the cladding functions as a nonstructural element whose primary environmental function is to control water penetration by allowing free movement of air for pressure equalization. Therefore, the exterior cladding in a pressure-equalized wall is referred to as a *screen*—or, more commonly, as a *rain screen*.

PRACTICAL LIMITATIONS OF A RAIN-SCREEN WALL

Theoretically, the exterior cladding in a pressure-equalized drainage wall should not be subjected to any wind load. In practice, however, it is not possible to achieve a completely load-free cladding. The reason is that pressure equalization does not occur instantaneously. It takes some time for pressure equalization to take place, depending on how rapidly the outside air can move into the intervening air space. If the area of openings in the wall is large, pressure equalization will be rapid. In the case of a small opening area, pressure equalization will be slow.

In other words, there is a time lag between a change in the outside pressure and the corresponding change in air space pressure. During this period (when pressure equalization is taking place), the cladding is subjected to wind loads. If there is no further change in the outside pressure, the air space and the outside will continue to be under equal pressures.

However, wind in a storm or hurricane occurs in gusts, so exterior air pressure changes almost continuously. This disturbs pressure equalization in a drainage wall. Therefore, the cladding is constantly subjected to wind loads, although the magnitude of the wind load on the cladding of a pressure-equalized wall is smaller than that on a non-pressure-equalized wall.

AIRTIGHT BACKUP WALL

Once the pressure in the air space is equalized with respect to the pressure on the wall's facade, no air movement will occur in the space (because any movement of air implies the existence of a pressure differential). The consequence of this fact is that the rain-screen principle works only if the backup is completely airtight. If the backup has openings, air will move from the air space into the enclosure, implying the existence of a pressure differential (hence, the absence of pressure equalization).

If the air is able to move into the enclosure through the backup wall, water may be sucked into the enclosure. Therefore, in a pressure-equalized wall, the backup wall must be made airtight. This is usually achieved by sealing all the joints in the backup wall and/or providing an air barrier. The air barrier is usually placed on the outside face of the backup wall so that it can also function as the damp-proofing layer.

COMPARTMENTALIZATION OF THE AIR SPACE

Another cause of air movement in an intervening air space is shown in Figure 27.9. Under the action of wind, the windward facade is under positive pressure and the side facades are under negative pressure. If the air space is continuous from one facade to the other, air will move through the space as shown, negating attempts at pressure equalization.

Therefore, the air space of a pressure-equalized drainage wall must be closed at wall corners. This is usually achieved by using a continuous vertical closure at the corners of the air space, Figure 27.10. A closed-cell compressible filler, such as neoprene sponge, may be used as the closure material.

In addition to providing vertical closures at wall corners, the air space should be closed by horizontal closures. In fact, the air space should be subdivided into independent compartments. The compartmentalization is in response to the variation of wind pressure over the building's facade. Wind pressure is greater at upper floors of a building than at lower floors, and is greater at edges and corners of the building than in the middle (see Section 3.5). If the air space is not compartmentalized, the pressure inequality over the facade will generate air movement inside the space.

Each compartment should have openings in the cladding at the top and bottom so that pressure equalization can take place. The openings should preferably be far enough away

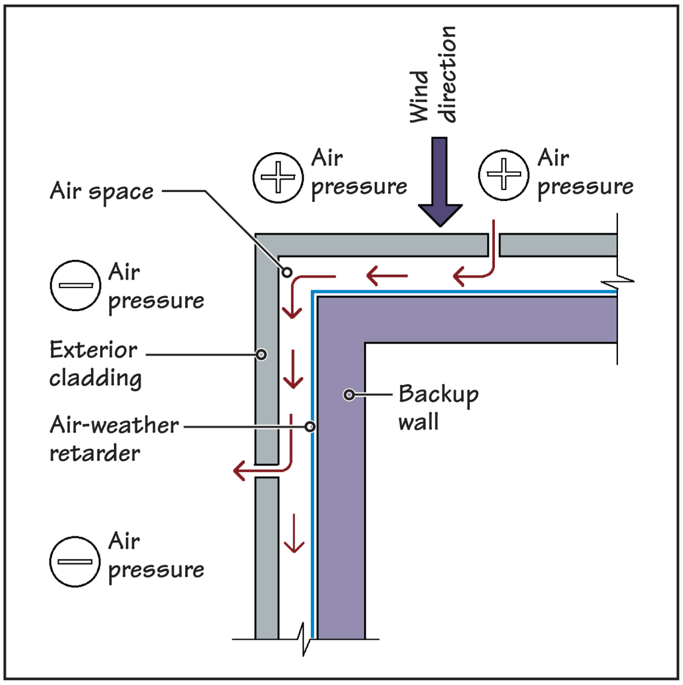

Wind direction
Air space
Air pressure
Air pressure
Air pressure
Exterior cladding
Backup wall
Air-weather retarder
Air pressure

FIGURE 27.9 Because wind produces positive pressure on the windward wall and negative pressure on other walls of a building, the air in a continuous air space will circulate and move in and out through weep holes and other openings (joints, cracks, etc.) in the cladding. This makes it impossible to achieve pressure equalization between the outside and the air space.

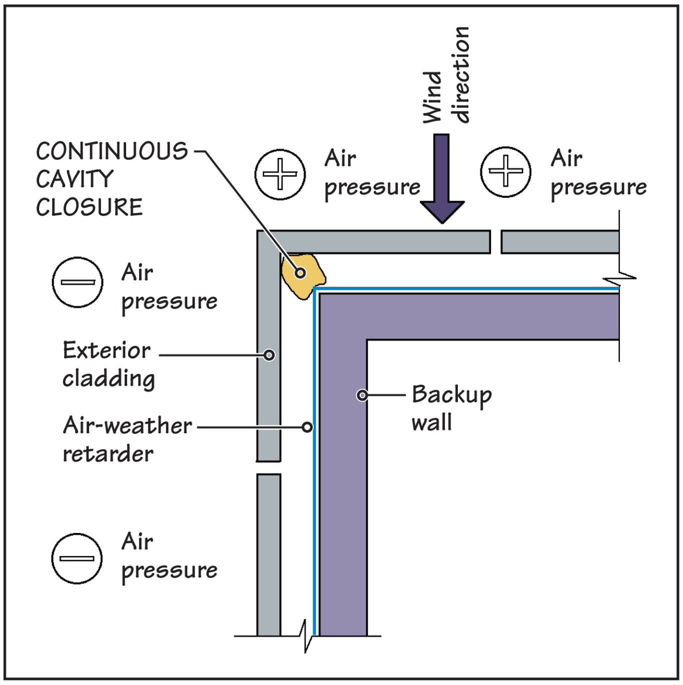

Wind direction
CONTINUOUS CAVITY CLOSURE
Air pressure
Air pressure
Air pressure
Exterior cladding
Backup wall
Air-weather retarder
Air pressure

FIGURE 27.10 To prevent air movement within the air space, the air space should be divided into small sections with continuous cavity closures, particularly at corners and floor levels.

from each other to prevent airflow short-circuiting in the compartment. Each compartment should also be relatively small and should be independently drained by weep holes. Although preferable, it is not necessary that air space closures form absolutely airtight compartments. In summary, an ideal rain-screen wall should consist of the following three water infiltration-control features:

1. Voids in cladding for pressure equalization in the air space
2. Compartmentalization of the air space
3. Airtight backup wall

27.4 CONTINUOUS INSULATION AND EXTERIOR CLADDING

Several exterior cladding details are undergoing changes due to the requirement of the International Energy Conservation Code (IECC) for continuous envelope insulation. The minimum prescriptive R-value requirements for continuous insulation vary with the climate zone. The least R-value requirement for continuous insulation is for Zone 1 and the highest value for Zone 8.

The purpose of continuous insulation is to eliminate thermal bridges in the envelope that can substantially reduce the effectiveness of insulation (see Sections 5.11 and 5.16). The requirement asks for an uninterrupted blanket of insulation over the entire envelope. Fasteners and hardware devices for connections, such as clip angles and clip channels, are excluded from this requirement.

The details illustrating the use of continuous envelope insulation are given in Chapters 28 and 29. However, the reader may recall from Section 5.15 that if the building has been modeled for energy use in terms of whole building performance to conform with the IECC, the prescriptive requirement of continuous insulation may be ignored and the traditional envelope details may be used.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The coping on a roof parapet is generally
   - **a.** sloped toward the interior (roof).
   - **b.** sloped toward the outside.
   - **c.** sloped on both sides.
   - **d.** (a), (b), or (c).
   - **e.** dead flat.
2. The coping on a masonry fence wall is generally
   - **a.** sloped toward the interior.
   - **b.** sloped toward the outside.
   - **c.** sloped on both sides.
   - **d.** (a), (b), or (c).
   - **e.** dead flat.
3. A drip mechanism at the underside of a projecting horizontal surface counters the effect of
   - **a.** gravity.
   - **b.** adhesive forces between water molecules and the building surface.
   - **c.** cohesive forces between water molecules.
   - **d.** cohesive forces between water molecules and the building surface.
   - **e.** kinetic energy.
4. A capillary break is a
   - **a.** vertical barrier between two abutting surfaces of different materials.
   - **b.** horizontal barrier between two abutting surfaces of different materials.
   - **c.** wider space in an otherwise narrow joint.
   - **d.** narrow space in an otherwise wide joint.
   - **e.** none of the above.
5. Z-flashing is effective in
   - **a.** a horizontal butt joint in cladding.
   - **b.** a vertical butt joint in cladding.
   - **c.** a horizontal lapped joint in cladding.
   - **d.** a vertical lapped joint in cladding.
   - **e.** all of the above.
6. In terms of water infiltration, the exterior masonry walls in historic buildings functioned as
   - **a.** waterproof walls. **b.** drainage walls.
   - **c.** face-sealed barrier walls. **d.** dam walls.
   - **e.** none of the above.
7. The most important feature of an (exterior) drainage wall is
   - **a.** exterior cladding.
   - **b.** waterproofing of the backup wall.
   - **c.** flashing.
   - **d.** weep holes.
   - **e.** all of the above.
8. Metal anchors are needed to transfer lateral loads to the backup wall in
   - **a.** some veneer walls. **b.** all veneer walls.
9. A curtain wall is separated from the structural frame of the building by a minimum of
   - **a.** 1 in. **b.** 2 in.
   - **c.** 3 in. **d.** 4 in.
   - **e.** none of the above.
10. A curtain wall is typically used in buildings whose structural system consists of a
    - **a.** load-bearing masonry wall structure.
    - **b.** load-bearing reinforced-concrete wall structure or load-bearing masonry wall structure.
    - **c.** reinforced-concrete frame structure or steel-frame structure.
    - **d.** steel-frame structure or load-bearing masonry wall structure.
    - **e.** all of the above.
11. A backup wall is required in a
    - **a.** curtain wall. **b.** veneer wall.
    - **c.** infill wall. **d.** all of the above.
12. Suction that pulls wind-driven rain into the air space of a drainage wall takes place on the windward face of a wall.
    - **a.** True **b.** False
13. In an ideal pressure-equalized drainage wall,
    - **a.** the cladding resists all of the wind load.
    - **b.** the backup resists all of the wind load.
    - **c.** the backup is provided with openings to equalize air pressure in the air space.
    - **d.** the joints in the cladding are sealed to control water infiltration.
    - **e.** all of the above.
14. An ideal pressure-equalized drainage wall is also referred to as a
    - **a.** pressure-screen wall. **b.** wind-screen wall.
    - **c.** no-pressure wall. **d.** rain-screen wall.
    - **e.** all of the above.
15. For a pressure-equalized drainage wall to function effectively, the air space must be continuous from floor to floor.
    - **a.** True **b.** False

REVIEW QUESTIONS

1. Using a sketch and notes, explain what a capillary break is and where it is commonly used.
2. Explain the differences between a barrier wall and a drainage wall.
3. Using sketches and notes, explain the important features of a drainage-type exterior wall.
4. Using sketches and notes, explain the difference between an anchored veneer and an adhered veneer.
5. Using sketches and notes, explain the salient features of a pressure-equalized drainage wall.
6. Explain why the air space in a pressure-equalized drainage wall must be compartmentalized.

CHAPTER 28

Exterior Wall Cladding–II (Masonry, Precast Concrete, and GFRC)

CHAPTER OUTLINE

28.1 ANCHORED MASONRY VENEER ASSEMBLY—GENERAL CONSIDERATIONS

28.2 BRICK VENEER WITH A CMU OR CONCRETE BACKUP WALL

28.3 BRICK VENEER WITH A STEEL STUD BACKUP WALL

28.4 CMU BACKUP VERSUS STEEL STUD BACKUP

28.5 AESTHETICS OF BRICK VENEER

28.6 PRECAST CONCRETE (PC) CURTAIN WALL

28.7 CONNECTING THE PC CURTAIN WALL TO A STRUCTURE

28.8 BRICK- AND STONE-FACED PC CURTAIN

28.9 DETAILING A PC CURTAIN WALL

28.10 GLASS FIBER–REINFORCED CONCRETE (GFRC) CURTAIN WALL

28.11 FABRICATION OF GFRC PANELS

28.12 DETAILING A GFRC CURTAIN WALL

This is the first of the two chapters on exterior wall finishes; it includes masonry veneer, precast concrete, and glass fiber–reinforced concrete (GFRC). Other exterior wall finishes—stucco, exterior insulation and finish systems (EIFS), stone cladding, and insulated metal panel walls—are discussed in the next chapter (Chapter 29).

ANCHORED MASONRY VENEER AND ADHERED MASONRY VENEER

Masonry veneer may be either (a) anchored masonry veneer or (b) adhered masonry veneer. In this chapter, only anchored masonry veneer is covered. Adhered masonry veneer is discussed in the following chapter because its detailing and construction processes are similar to those of stucco.

28.1 ANCHORED MASONRY VENEER ASSEMBLY—GENERAL CONSIDERATIONS

Among all contemporary exterior wall cladding systems, masonry (brick, CMU, and stone) veneer is most widely used, and within the three masonry veneer systems, *brick veneer* is by far the most popular system. Its popularity lies in its durability, fire resistance, and aesthetic appeal.

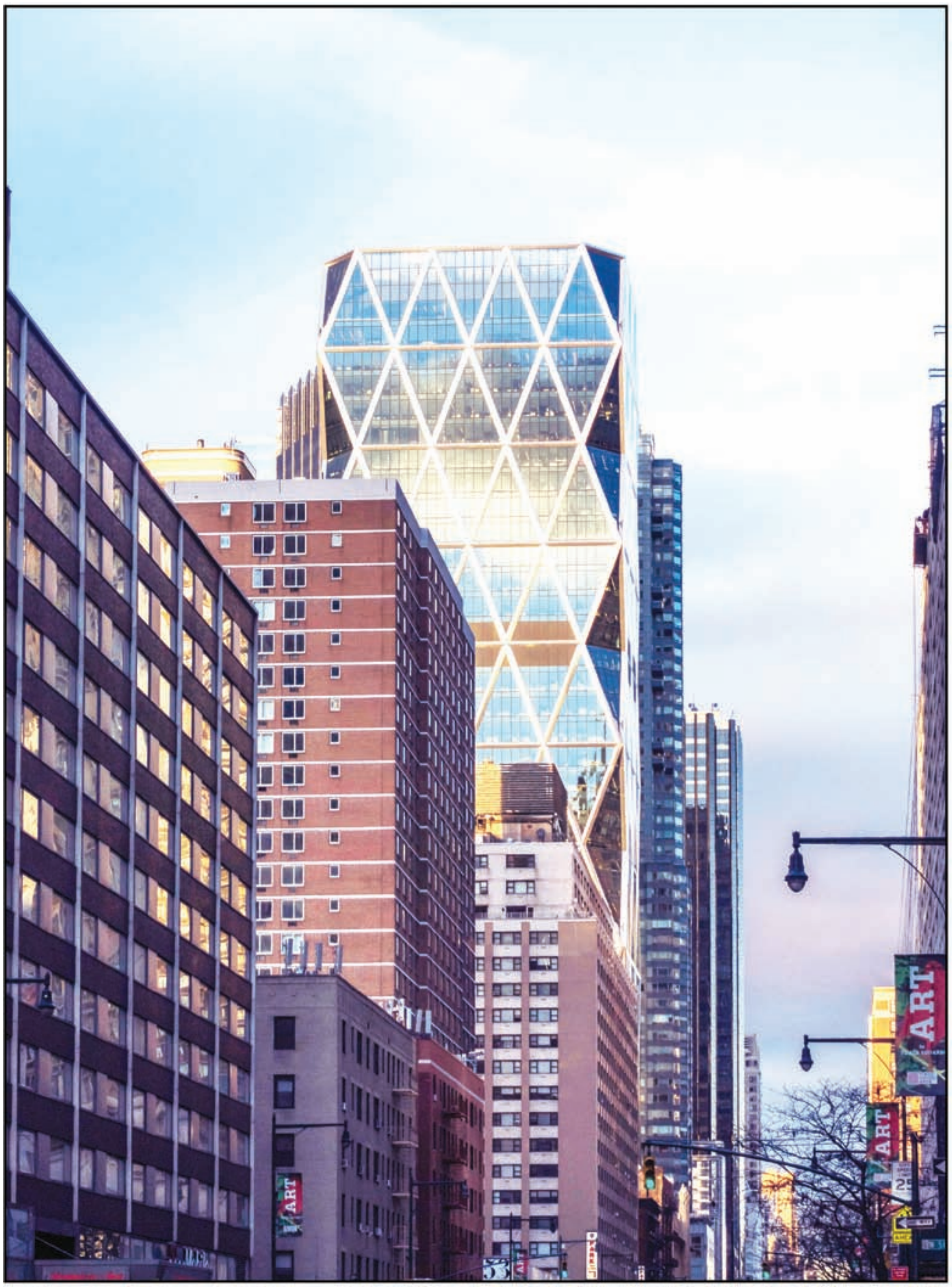


FIGURE 28.1 Because of its versatility, durability, economic advantages, and aesthetic appeal, brick veneer is among the most widely used facades for all types of buildings, particularly for mid-rise and high-rise buildings, as this New York City street shows. Seen in the background in this photo is the glass-clad Hearst Tower, Design Architect: Foster and Partners; Architect of Record: Adamson Associates. (Photo by Ed Rooney/Alamy Stock Photo.)

Additionally, the system requires almost no maintenance and can be used for buildings of all heights and complexity—from high-rise to low-rise and from simple rectilinear facades to intricate ones. A cursory survey of building facades in North American cities confirms this assertion, Figure 28.1.

A brick veneer generally consists of a single-wythe brick wall (generally 4 in. nominal thickness). The backup wall used with brick veneer may be load-bearing or non-load-bearing and may consist of one of the following:

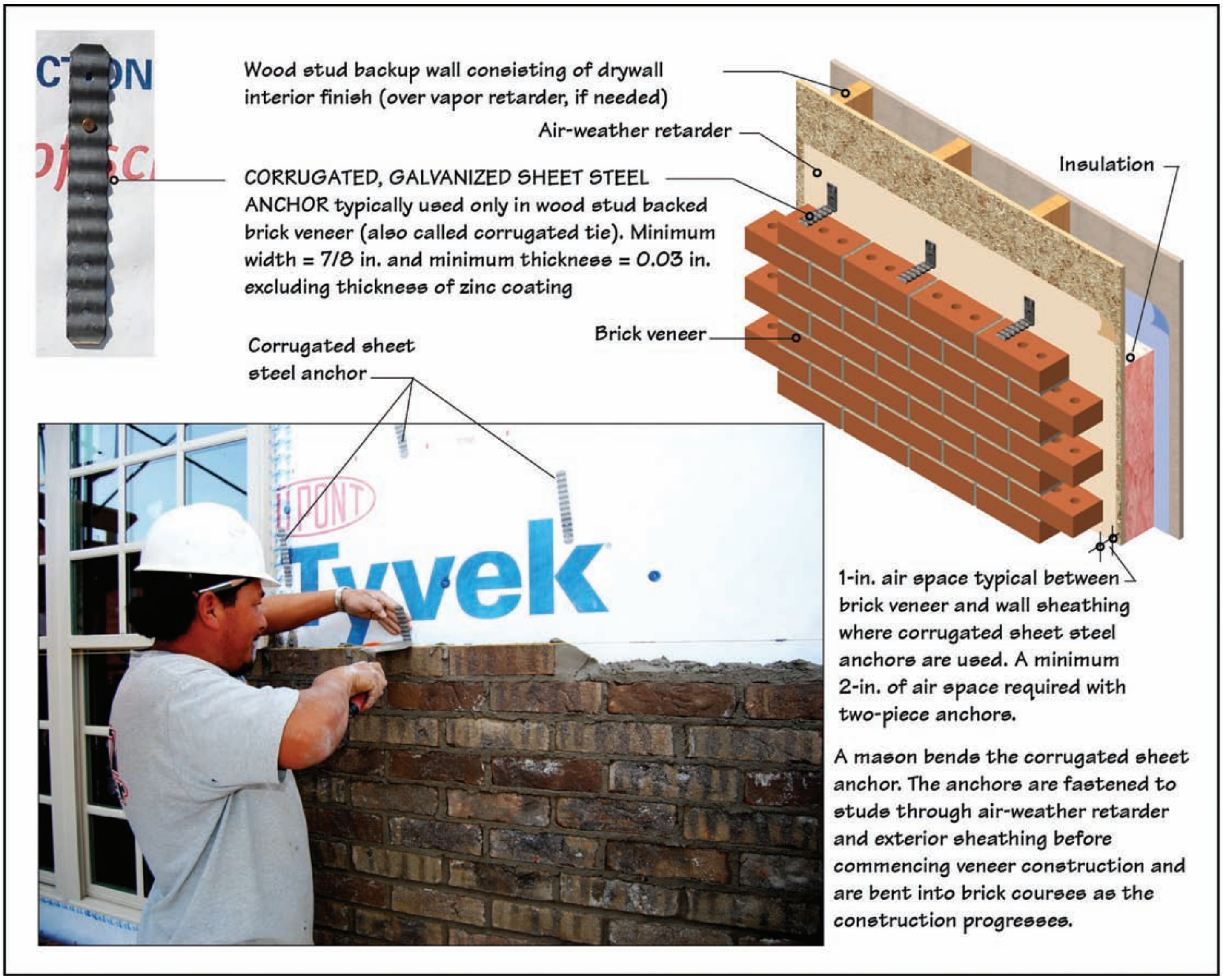
- Wood or cold-formed steel stud
- Concrete masonry
- Reinforced concrete

A wood stud (or steel stud) load-bearing backup wall, Figure 28.2, is typically used in low-rise residential construction. Concrete masonry, non-load-bearing steel stud, and reinforced-concrete backup walls are generally used in commercial construction. In fact, brick veneer with concrete masonry backup is the wall assembly of choice for many building types, such as schools, university campus buildings, and offices.

The discussion presented here refers to brick veneer. It can, however, be extended to include other (CMU and stone) masonry veneers with little or no change.

ANCHORS

In a brick veneer assembly, the veneer is connected to the backup wall with steel anchors, which transfer the lateral load from the veneer to the backup wall. In this load transfer, the



Wood stud backup wall consisting of drywall interior finish (over vapor retarder, if needed)

CORRUGATED, GALVANIZED SHEET STEEL ANCHOR typically used only in wood stud backed brick veneer (also called corrugated tie). Minimum width = 7/8 in. and minimum thickness = 0.03 in. excluding thickness of zinc coating

1-in. air space typical between brick veneer and wall sheathing where corrugated sheet steel anchors are used. A minimum 2-in. of air space required with two-piece anchors.

A mason bends the corrugated sheet anchor. The anchors are fastened to studs through air-weather retarder and exterior sheathing before commencing veneer construction and are bent into brick courses as the construction progresses.

FIGURE 28.2 Brick veneer with a wood stud backup wall.

anchors are subjected to either axial compression or tension, depending on whether the wall is subjected to inward or outward pressure.

The anchors must, therefore, have sufficient rigidity and allow little or no movement in the plane perpendicular to the wall. However, because the veneer and the backup will usually expand or contract at different rates in their own planes, the design of anchors must accommodate upward-downward and side-to-side movement, Figure 28.3.

Anchors for a brick veneer wall assembly are, therefore, made of two pieces that engage each other. One piece is secured to the backup, and the other is embedded in the horizontal mortar joints of the veneer. An adjustable two-piece anchor should allow the veneer to move with respect to the backup in the plane of the wall but not perpendicular to it.

An exception to this requirement is a one-piece sheet steel corrugated anchor (Figure 28.2). The corrugations in the anchor enhance the bond between the anchor and the mortar, increasing the anchor's pullout strength. However, the corrugations weaken the anchor in compression by making it more prone to buckling. A one-piece corrugated anchor is recommended for use only in low-rise, wood light-frame buildings in low-wind and low-seismic-risk locations.

Galvanized steel is commonly used for anchors, but stainless steel is recommended where durability is an important consideration and/or where the environment is unusually corrosive.

The spacing of anchors should be calculated based on the lateral load and the strength of the anchor. However, the maximum spacing for a one-piece corrugated anchor or an adjustable two-piece wire anchor (wire size W1.7) is limited by the codes to one anchor for every 2.67 ft^2 [Ref. 28.1]. Additionally, the anchors should not be spaced more than 32 in. on center horizontally and not more than 18 in. vertically, Figure 28.4.

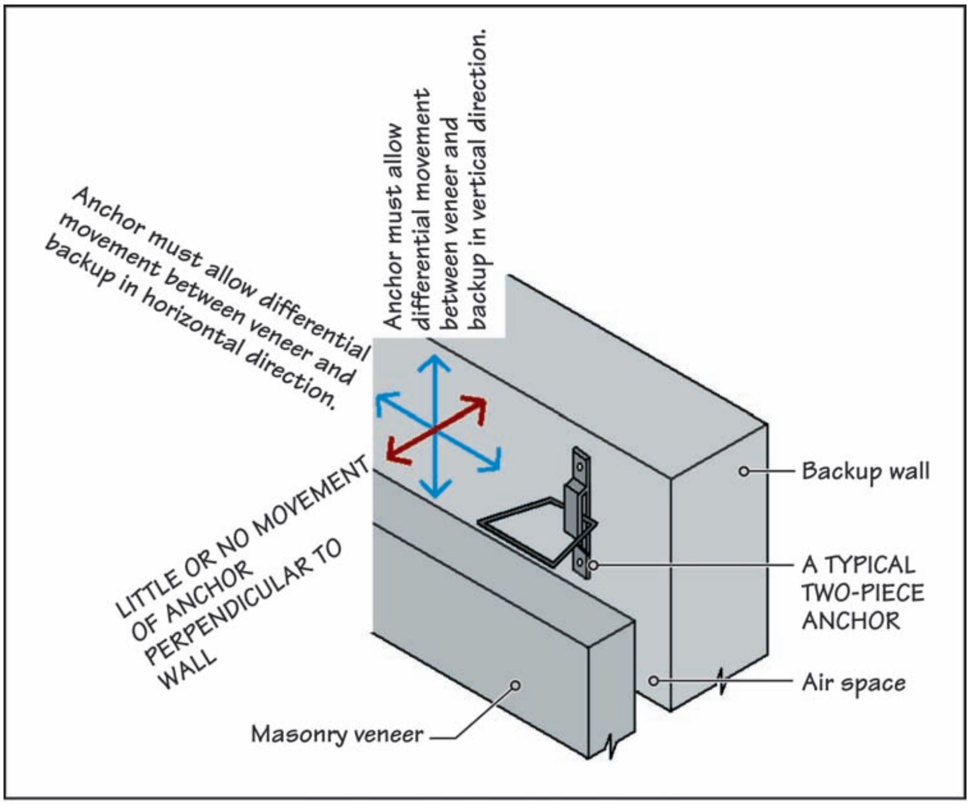

Anchor must allow differential movement between veneer and backup in horizontal direction.
Anchor must allow differential movement between veneer and backup in vertical direction.
LITTLE OR NO MOVEMENT OF ANCHOR PERPENDICULAR TO WALL
Backup wall
A TYPICAL TWO-PIECE ANCHOR
Air space
Masonry veneer

FIGURE 28.3 Adjustability requirements in various directions of a two-piece anchor.

AIR SPACE

An air space of 2 in. (clear) is recommended for brick veneer. Thus, if there is $1\frac{1}{2}$-in.-thick (rigid) insulation between the backup wall and the veneer, the backup and the veneer must be spaced $3\frac{1}{2}$ in. apart so that the air space is 2 in. clear, Figure 28.5.

In a narrower air space, there is a possibility that if the mortar squeezes out into the air space during brick laying, it may bridge over and make a permanent contact with the backup wall. A 2-in. air space reduces this possibility. In a wood-stud-backed wall assembly with one-piece corrugated anchors, however, a 1-in. air space is commonly used (Figure 28.2).

The maximum distance between the veneer and the backup wall is limited by the masonry code to $4\frac{1}{2}$ in. unless the anchors are specifically engineered to withstand the compressive forces imposed on them by the lateral load. With a large gap between the veneer and the backup wall, the anchors are more prone to buckling failure.

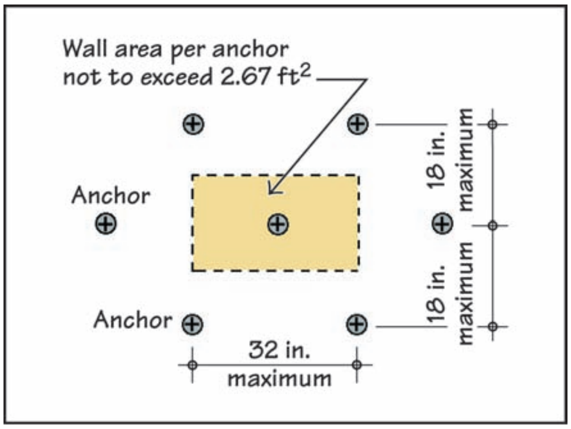

Wall area per anchor not to exceed 2.67 ft²
Anchor
Anchor
18 in. maximum
18 in. maximum
32 in. maximum

FIGURE 28.4 Anchor spacing should be determined based on the lateral load and the strength of anchors. However, for a one-piece corrugated sheet anchor or a two-piece adjustable wire anchor (wire size W1.7), the maximum spacing allowed is as shown. W1.7 means that the cross-sectional area of wire = 0.017 in.^{2} (see Section 21.13). Anchors should preferably be staggered, as shown.

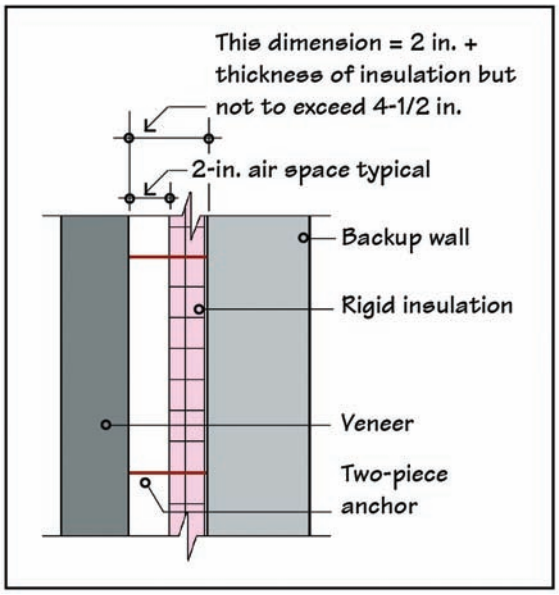

This dimension = 2 in. + thickness of insulation but not to exceed 4-1/2 in.
2-in. air space typical
Backup wall
Rigid insulation
Veneer
Two-piece anchor

FIGURE 28.5 A minimum 2-in.-wide air space is required except in low-rise buildings, where a 1-in.-wide air space is common. The gap between the veneer and the backup wall should not exceed 4 in. for standard veneer ties. For a wider gap, the ties must be engineered.

SUPPORT FOR BRICK VENEER—SHELF ANGLES ANCHORED TO STRUCTURAL FRAME

The dead load of brick veneer may be borne by the wall foundation without any support at intermediate floors up to a maximum height of 30 ft above ground. Uninterrupted foundation-supported veneer is commonly used in one- to three-story wood or cold-formed steel-frame buildings, Figure 28.6(a). In these buildings, the air space is continuous from the foundation to the roof level, and the entire load of the veneer bears on the foundation. A $1\frac{1}{2}$-in. depression, referred to as the *brick ledge*, is commonly created in the foundation to receive the first course of the veneer.

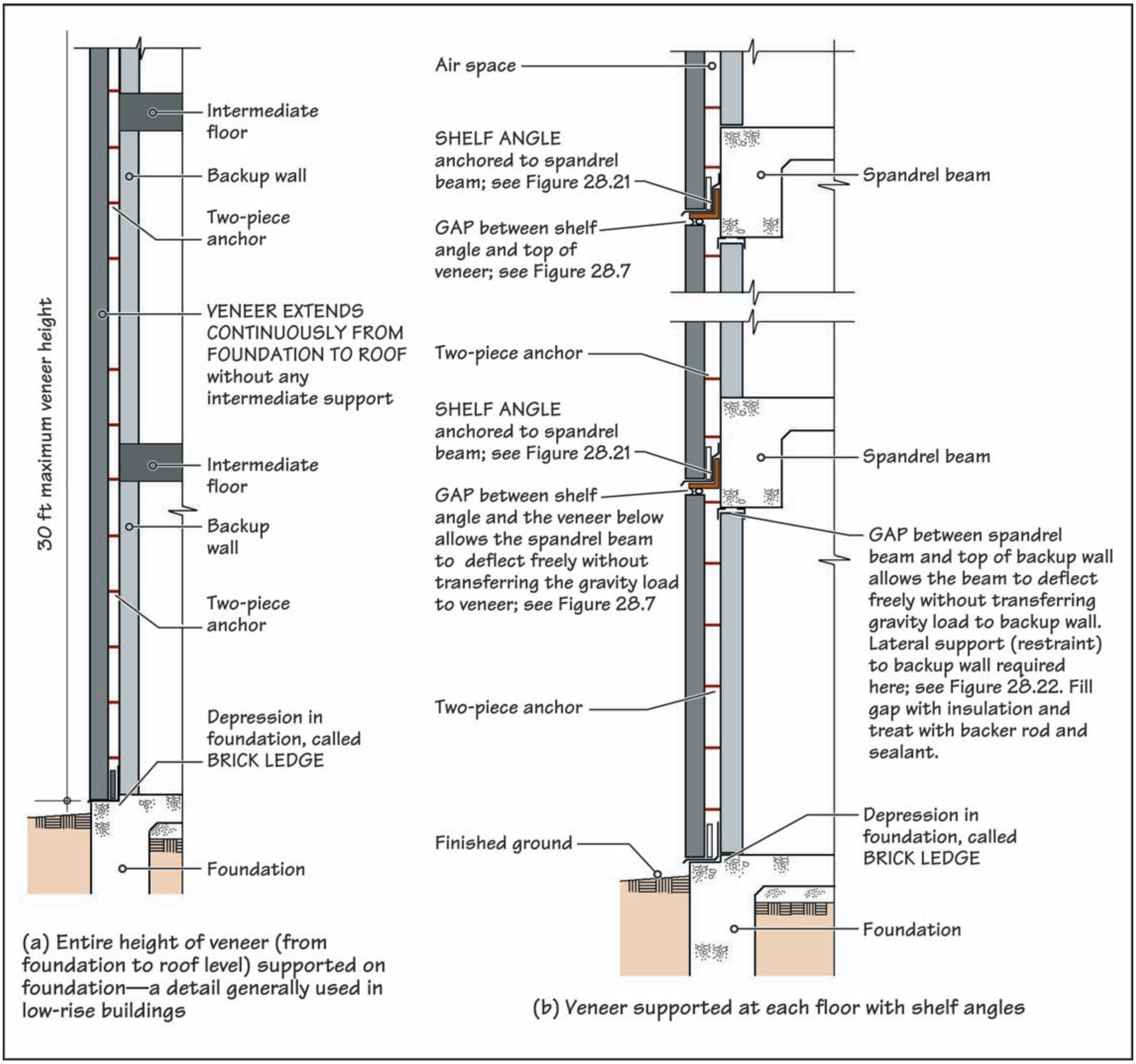
In mid- and high-rise buildings, the veneer is generally supported at each floor using (preferably hot-dip galvanized) steel *shelf angles* (also referred to as *relieving angles*). Shelf angles are supported by, and anchored to, the building's structure. In a frame structure, the shelf angles are anchored (welded or bolted) to the spandrel beams, Figure 28.6(b). In a load-bearing wall structure, the shelf angles are anchored to the exterior walls. The details of the anchorage of a shelf angle to the structure are given later in the chapter.

A gap should be provided between the top of the veneer and the bottom of the shelf angle. This gap accounts for the vertical expansion of brick veneer (after construction) and the deflection of the spandrel beam under live load changes, and must be determined by

NOTE

Brick Ledge

A brick ledge is the depression in the concrete foundation at the base of brick veneer and is generally $1\frac{1}{2}$ in. deep, because it is formed by 2-by lumber used as a block-out when placing concrete (Figure 28.6). The depression further prevents water intrusion into the backup wall.


30 ft maximum veneer height
Intermediate floor
Backup wall
Two-piece anchor
VENEER EXTENDS CONTINUOUSLY FROM FOUNDATION TO ROOF without any intermediate support
Intermediate floor
Backup wall
Two-piece anchor
Depression in foundation, called BRICK LEDGE
Foundation
Air space
SHELF ANGLE anchored to spandrel beam; see Figure 28.21
GAP between shelf angle and top of veneer; see Figure 28.7
Spandrel beam
Two-piece anchor
SHELF ANGLE anchored to spandrel beam; see Figure 28.21
GAP between shelf angle and the veneer below allows the spandrel beam to deflect freely without transferring the gravity load to veneer; see Figure 28.7
Spandrel beam
GAP between spandrel beam and top of backup wall allows the beam to deflect freely without transferring gravity load to backup wall. Lateral support (restraint) to backup wall required here; see Figure 28.22. Fill gap with insulation and treat with backer rod and sealant.
Two-piece anchor
Finished ground
Depression in foundation, called BRICK LEDGE
Foundation

(a) Entire height of veneer (from foundation to roof level) supported on foundation—a detail generally used in low-rise buildings

(b) Veneer supported at each floor with shelf angles

FIGURE 28.6 Dead load support for veneer.

the architect in consultation with the structural engineer. The gap should be treated with a backer rod and sealant, Figure 28.7. The veneer may project beyond the shelf angle, but the projection should not exceed one-third of the thickness of the veneer.

Shelf angles must not be continuous. A maximum length of about 20 ft is used for shelf angles, with nearly a $\frac{3}{8}$-in. gap between adjacent lengths to provide for thermal movement. The gap should ideally be at the same location as the vertical expansion joints in the veneer.

Lintel Angles—Loose-Laid

Whether the veneer is supported entirely on the foundation or at each floor, additional dead load support for the veneer is needed over wall openings. The lintels generally used over an opening in brick veneer are of steel (preferably hot-dip galvanized) angles, Figure 28.8. Unlike the shelf angles, lintel angles are not anchored to the building's structural frame but are simply placed (loose) on the veneer, Figure 28.9.

To allow the lintel to move horizontally relative to the brick veneer, no mortar should be placed between the lintel bearing and the brick veneer. Flashing and weep holes must be provided over lintels in exactly the same way as on the shelf angles.

Locations of Flashings and End Dams

As shown in Figure 28.8, flashings must be provided at all interruptions in the brick veneer:

- At the foundation level
- Over a shelf angle
- Over a lintel angle
- Under a window sill

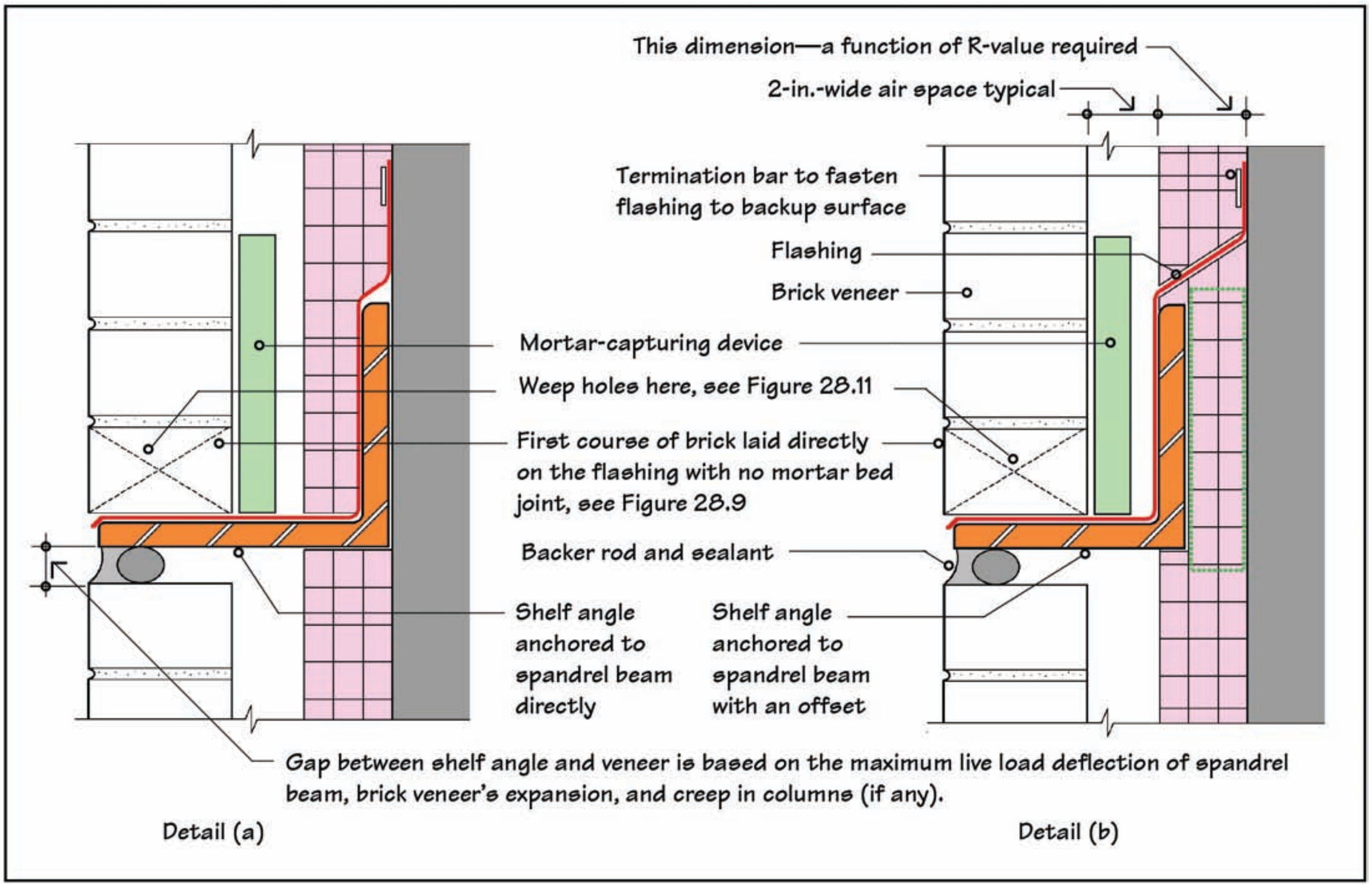

This dimension—a function of R-value required
2-in.-wide air space typical
Termination bar to fasten flashing to backup surface
Flashing
Brick veneer
Mortar-capturing device
Weep holes here, see Figure 28.11
First course of brick laid directly on the flashing with no mortar bed joint, see Figure 28.9
Backer rod and sealant
Shelf angle anchored to spandrel beam directly
Shelf angle anchored to spandrel beam with an offset
Gap between shelf angle and veneer is based on the maximum live load deflection of spandrel beam, brick veneer's expansion, and creep in columns (if any).
Detail (a)
Detail (b)

FIGURE 28.7 Schematic details at a typical shelf angle and its anchorage to building structure. The two details shown are essentially the same except that Detail (a) shows conventional anchorage of shelf angle to building structure that creates a continuous thermal bridge, substantially reducing the effective R-value of insulation. In Detail (b), the shelf angle is offset from building structure and anchored to it at intervals, reducing the effect of thermal bridges. The offset dimension is a function of the required R-value of insulation.

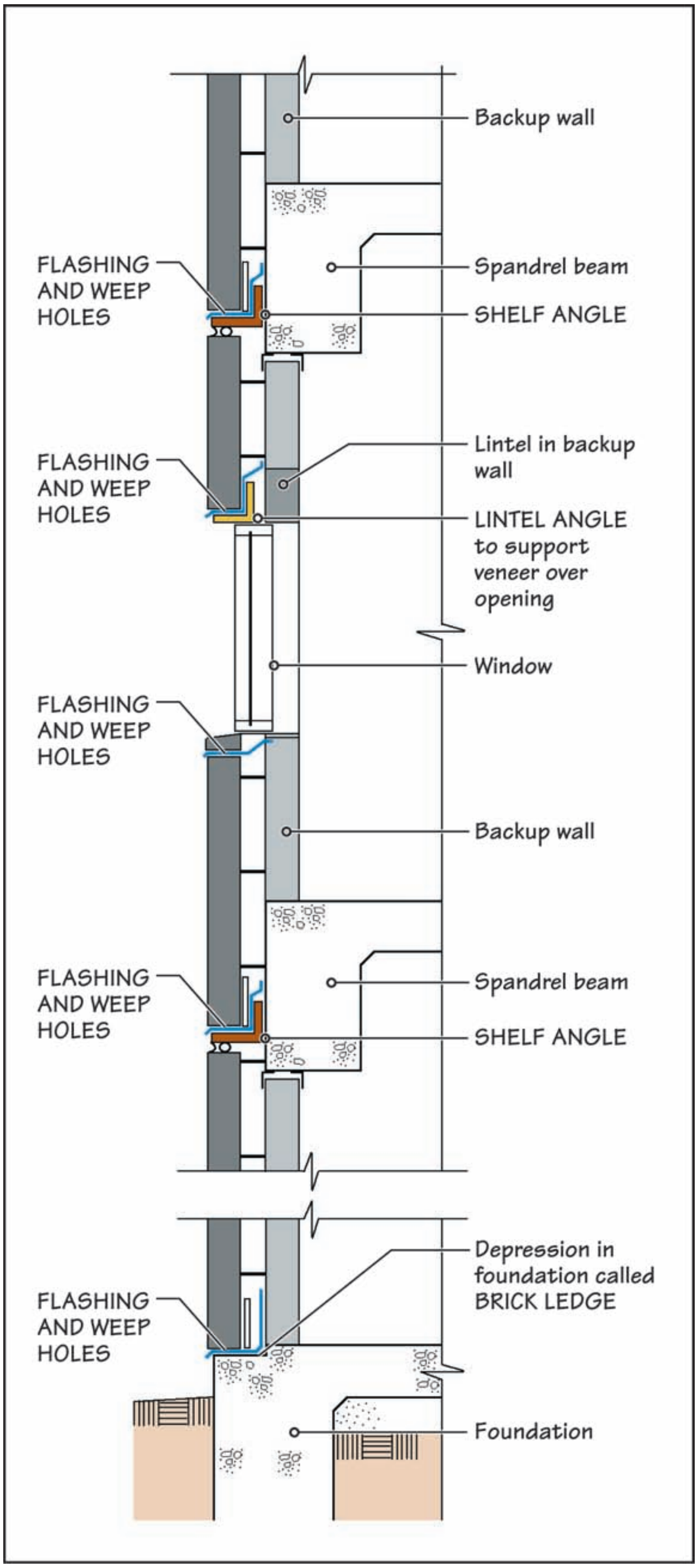
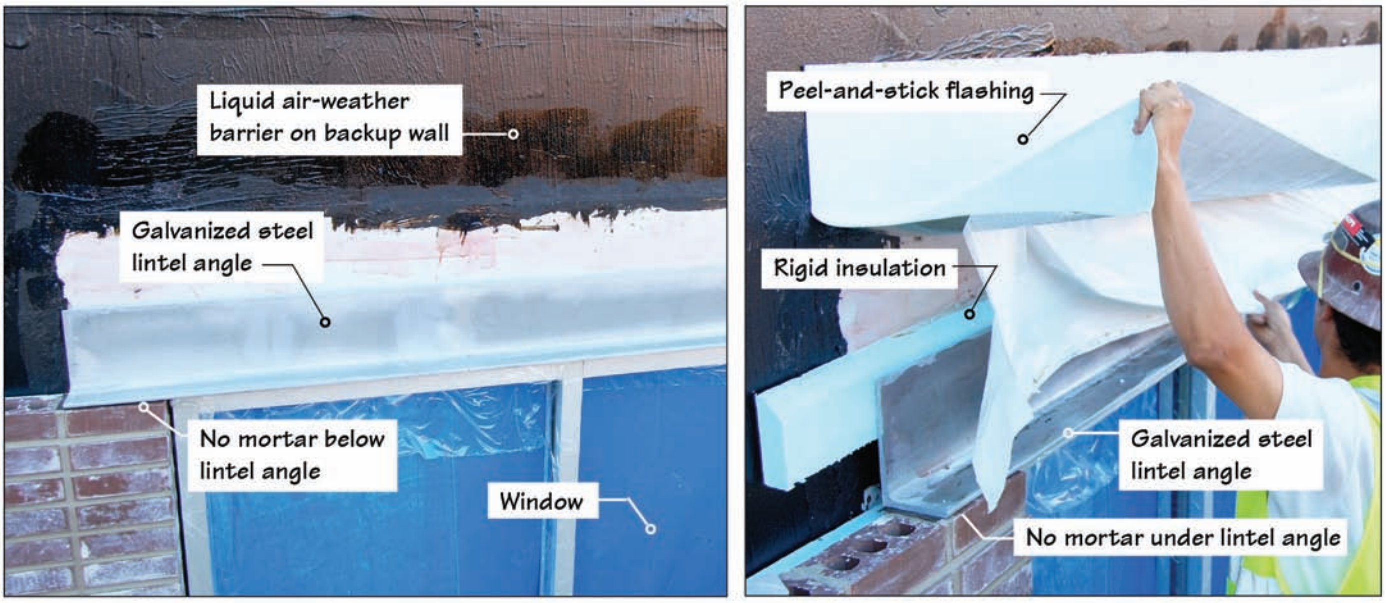

Backup wall
FLASHING AND WEEP HOLES
Spandrel beam
SHELF ANGLE
FLASHING AND WEEP HOLES
Lintel in backup wall
LINTEL ANGLE to support veneer over opening
Window
FLASHING AND WEEP HOLES
Backup wall
FLASHING AND WEEP HOLES
Spandrel beam
SHELF ANGLE
Depression in foundation called BRICK LEDGE
FLASHING AND WEEP HOLES
Foundation

FIGURE 28.8 A schematic section showing the locations of shelf angles, lintel angles, and flashings in a typical brick veneer assembly.

Joints between flashings must be sealed, and all flashings must be accompanied by weep holes. The flashing should preferably project out of the veneer face to ensure that the water will drain to the outside of the veneer (Figure 28.7). Where the flashing terminates, it must be turned up (equal to the height of one brick) to form a dam to prevent water from entering the air space, Figure 28.10. Alternatively, a separate end dam flashing may be used, as shown in Figure 28.9(c).

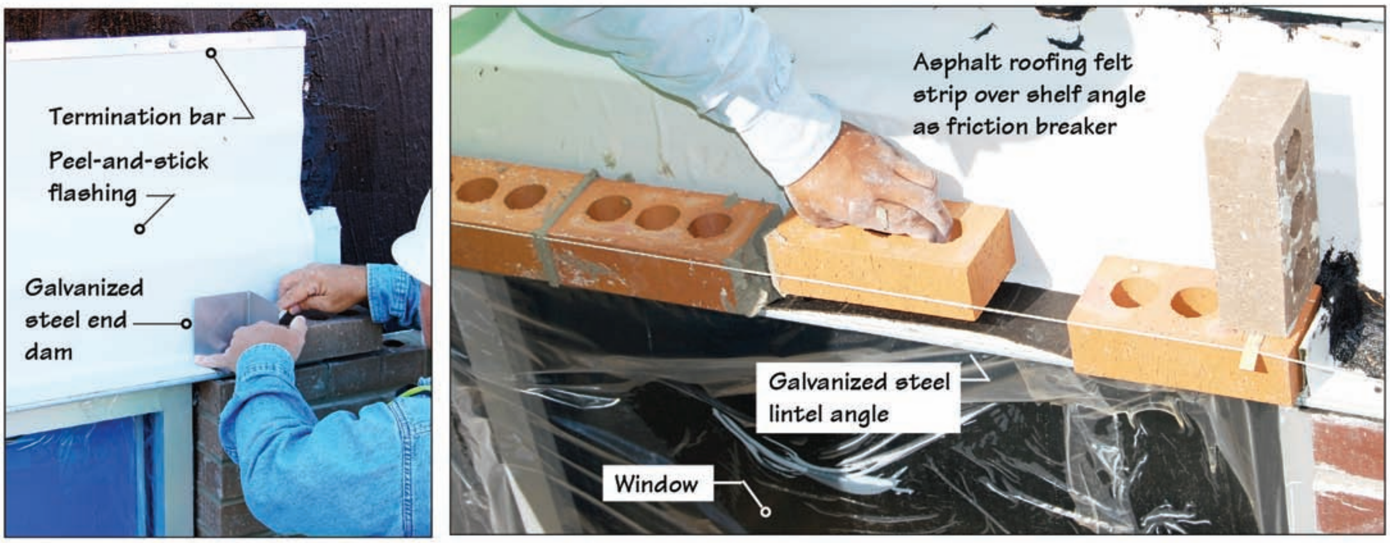
Flashing Materials

Flashing material must be impervious to water and resistant to puncture, tearing, and abrasion. Additionally, flashing must be flexible so that it can be bent to the required profile. Durability is also important because replacing failed flashing is cumbersome and expensive.


Liquid air-weather barrier on backup wall
Galvanized steel lintel angle
No mortar below lintel angle
Window
Peel-and-stick flashing
Rigid insulation
Galvanized steel lintel angle
No mortar under lintel angle

(a) Lintel angle bears on end sections of brick veneer with no mortar below it

(b) Installation of flashing over lintel angle


Termination bar
Peel-and-stick flashing
Galvanized steel end dam
Asphalt roofing felt strip over shelf angle as friction breaker
Galvanized steel lintel angle
Window

(c) Bricklayer placing galvanized steel end dam over flashing, anchored by the weight of brick courses to follow

(d) First course of bricks laid on lintel angle with mortared head joints but no mortar in bed joints

FIGURE 28.9 Lintel angles in a brick veneer wall. Note that the first course of veneer over flashing is laid without any mortar bed between bricks and flashing, see also Figure 28.7.

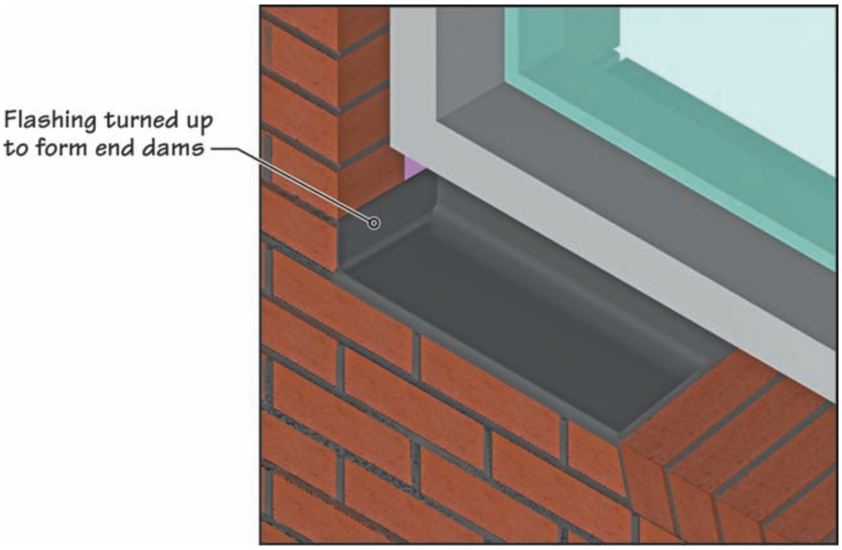

Flashing turned up to form end dams

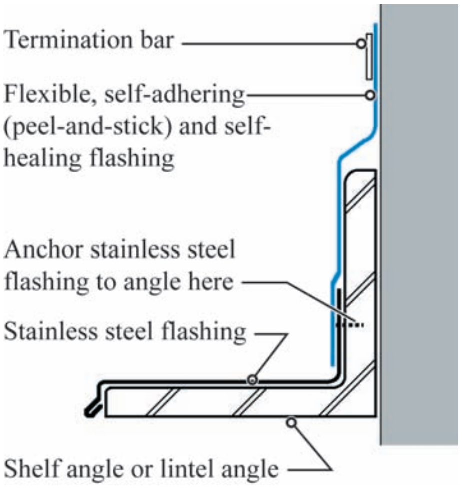
FIGURE 28.10 End dams in flashing, revealed by removing a few bricks of the window sill (in the rowlock course). Weep holes in the brick sill (over the flashing) are not shown for clarity.

Therefore, metal flashing must be corrosion resistant. Resistance to ultraviolet radiation is also necessary because the projecting part of the flashing is exposed to the sun. Commonly used flashing materials are as follows:

- Stainless sheet steel
- Copper sheet
- Plastics such as
  - Polyvinyl chloride (PVC)
  - Neoprene
  - Ethylene propylene diene monomer (EPDM)
- Composite flashing consisting of
  - Rubberized asphalt with cross-laminated polyethylene, typically available as self-adhering and self-healing flashing
  - Copper sheet laminated on both sides to asphalt-saturated paper or fiberglass felt

Copper and stainless steel are among the most durable flashing materials. Copper's advantage over stainless steel is its greater flexibility, which allows it to be bent to shape more easily. However, copper will stain light-colored masonry because of its corrosion, which yields a greenish protective cover (patina). Copper combination flashing, consisting of a copper sheet laminated to asphalt-saturated paper, reduces its staining potential.

A fairly successful flashing is a two-part flashing comprising a self-adhering, self-healing polymeric membrane and a stainless steel drip edge. The durability and rigidity of stainless steel makes a good drip edge, and the flexible, self-adhering membrane simplifies flashing installation.


Termination bar
Flexible, self-adhering (peel-and-stick) and self-healing flashing
Anchor stainless steel flashing to angle here
Stainless steel flashing
Shelf angle or lintel angle

NOTE

Weep Hole Spacing

A center-to-center spacing of 24 in. is generally used for weep holes when open-head joints are used. A spacing of 16 in. is used with weep holes consisting of wicks or tubes.

Construction and Spacing of Weep Holes

Weep holes must be provided immediately above the flashing. There are several different ways to provide weep holes. The simplest and most effective weep hole is an open vertical mortar joint (open-head joint) in the veneer, Figure 28.11.

To prevent insects and debris from lodging in the open-head joint, joint screens may be used. A joint screen is an L-shaped sheet metal or plastic element, Figure 28.12(a). Its vertical leg has louvered openings to let the water out, and the horizontal leg is embedded in the horizontal mortar joint of the veneer. The joint screen has the same width as the head joints. An alternative honeycombed plastic joint screen is also available, Figure 28.12(b).

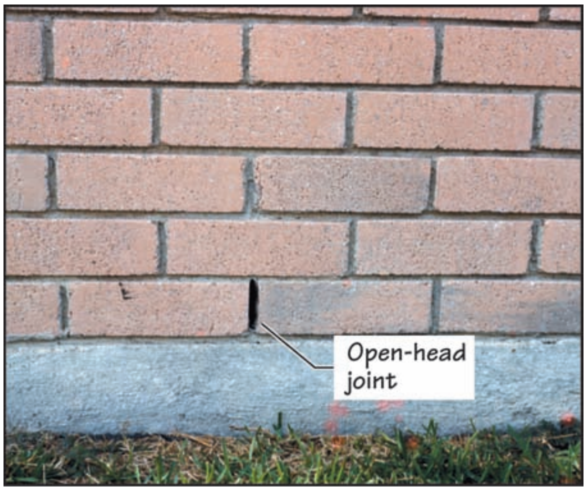

Open-head joint

FIGURE 28.11 Open-head joints as weep holes.

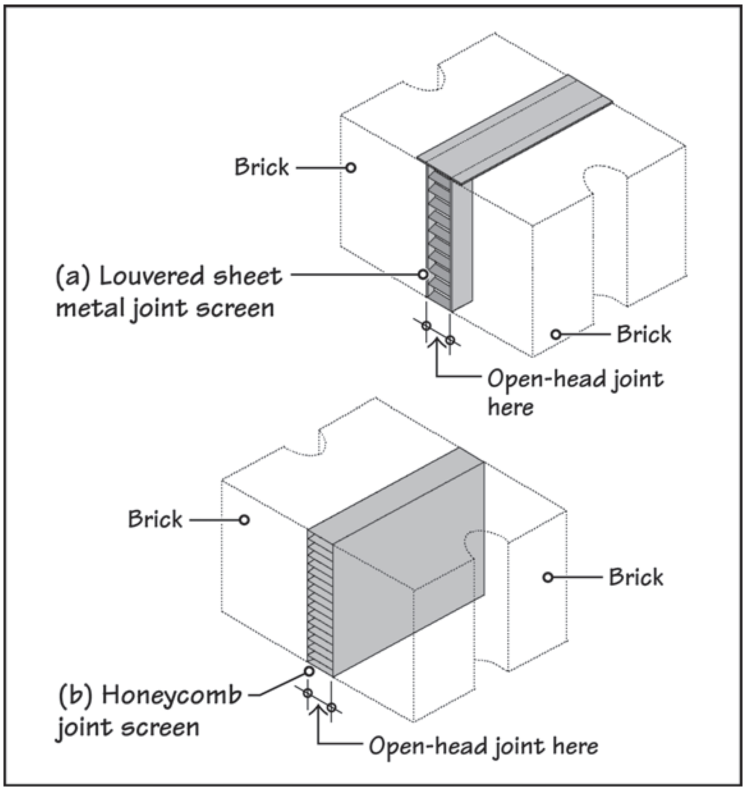

Brick
(a) Louvered sheet metal joint screen
Brick
Open-head joint here
Brick
Brick
(b) Honeycomb joint screen
Open-head joint here

FIGURE 28.12 Two alternative screens used with weep holes consisting of open-head joints.

Instead of the open-head joint, wicks or plastic tubes ($\frac{3}{8}$ in. diameter) may be used in a mortared-head joint. Wicks, which consist of cotton ropes, are embedded in head joints, Figure 28.13. They absorb water from the air space by capillary action and drain it to the outside. Their drainage efficiency is low.

Plastic tubes are better than wicks, but they do not function as well as open-head joints. They are placed in head joints with a rope inside each tube. The ropes are pulled out after the veneer has been constructed. This ensures that the air spaces of the tubes are not clogged by mortar droppings.

A sufficient number of weep holes must be provided for the drainage of the air space. Generally, a weep hole spacing of 24 in. is used with open-head joints; 16-in. spacing is used with wicks or tubes.

MORTAR DROPPINGS IN THE AIR SPACE—MORTAR-CAPTURING DEVICE

For the air space to function as an effective drainage layer, it is important to minimize mortar droppings in the air space. Excessive buildup of mortar in the air space bridges the space. Additionally, the weep holes function well only if they are not clogged by mortar droppings. Poor bricklaying practice can result in substantial accumulations of mortar on the flashing. Care in bricklaying to reduce mortar droppings is therefore essential.

Additional measures must also be incorporated to keep the air space unclogged. An earlier practice was to use a 2-in.-thick bed of pea gravel over the flashing. This provides a drainage bed that allows the water to percolate to the weep holes.

A better alternative is to use a *mortar-capturing device* in the air space immediately above the flashing. This device consists of a mesh made of polymeric strands, which trap the droppings and suspend them permanently above the weep holes, Figure 28.14. The use of a mortar-capturing device allows water in the air space to percolate freely through mortar droppings to reach the weep holes.

CONTINUOUS VERTICAL EXPANSION JOINTS IN BRICK VENEER

As stated in Section 9.8, brick walls expand after construction. Therefore, a brick veneer must be provided with continuous vertical expansion joints at intervals, Figure 28.15.

The maximum recommended spacing [Ref. 28.2] of vertical expansion joints is as follows:

- 25 ft between wall panels without windows
- 20 ft between wall panels with punched windows
- 10 ft from a wall corner

The joints are detailed so that sealant and backer rods replace mortar joints for the entire length of the continuous vertical expansion joint, allowing the bricks on both sides of the joint to move while maintaining a waterproof seal, Figure 28.16. The width of the expansion joint is $\frac{1}{2}$ in. (minimum) to match the width of the mortar joints.

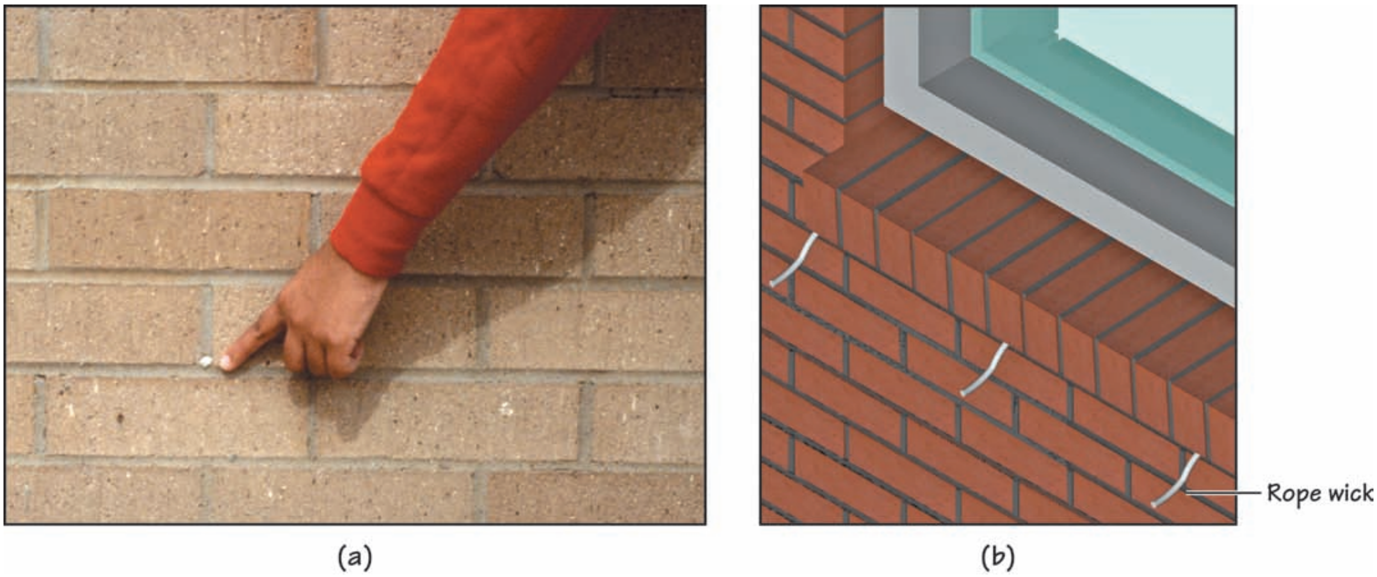


FIGURE 28.13 **(a)** Wicks as weep holes. **(b)** The wick ropes will be trimmed similar to those shown in (a).

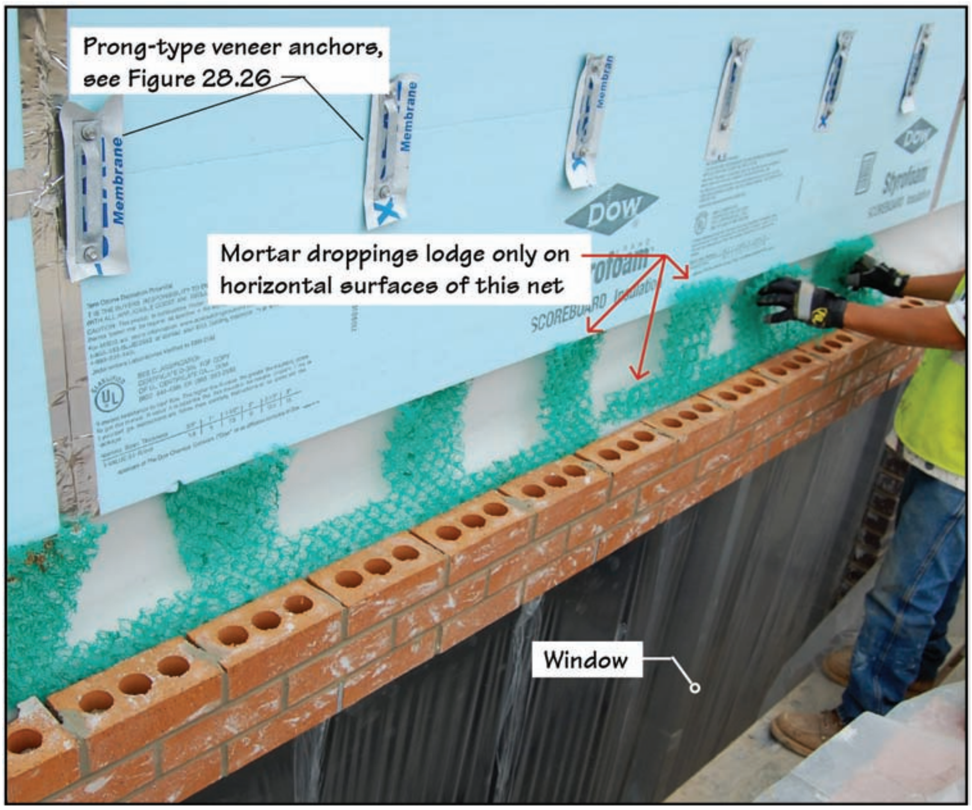

Prong-type veneer anchors, see Figure 28.26
Mortar droppings lodge only on horizontal surfaces of this net
Window

FIGURE 28.14 A mortar-capturing device is available in different types depending on its manufacturer. The one seen in this photograph consists of a 1-in.-thick, specially profiled woven mesh of synthetic wires (green mesh) so that the mortar droppings are captured by the horizontal surfaces of the mesh. The remaining areas of the mesh are left free of droppings so that the rainwater entering the air space is able to drain through the mesh to the bottom of the air space and exit through the weep holes.

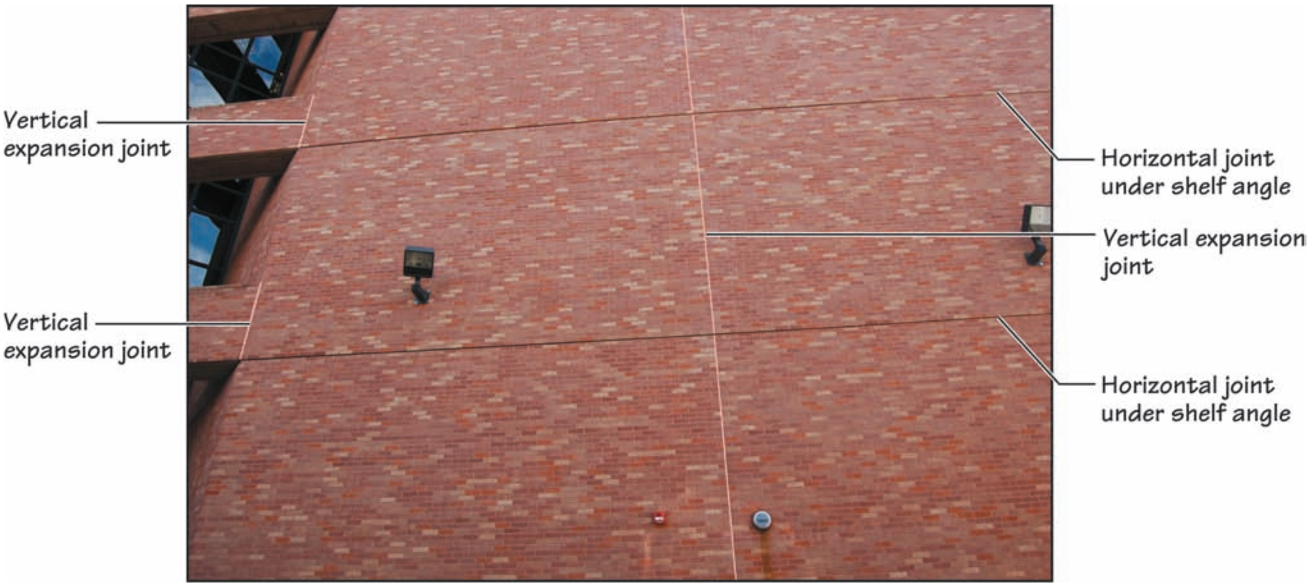

Vertical expansion joint
Vertical expansion joint
Horizontal joint under shelf angle
Vertical expansion joint
Horizontal joint under shelf angle

FIGURE 28.15 Continuous vertical expansion joints in brick veneer. Also note the continuous horizontal joints under the shelf angles.

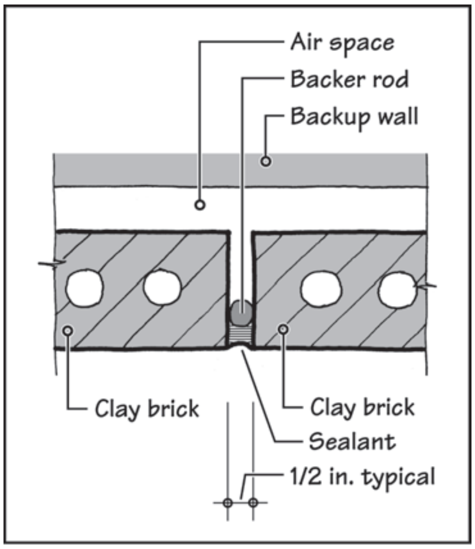

Air space
Backer rod
Backup wall
Clay brick
Clay brick
Sealant
1/2 in. typical

FIGURE 28.16 Detail plan of a vertical expansion joint in brick veneer. This illustration is the same as Figure 9.17.

With vertical expansion joints and the gaps under shelf angles (which function as horizontal expansion joints), a brick veneer essentially consists of individual brick panels that can expand and contract horizontally and vertically without stressing the backup wall or the building's structure.

MORTAR TYPE AND MORTAR JOINT PROFILE

Type N mortar is generally specified in all-brick veneer except in seismic zones, where Type S mortar may be used (see Section 24.2). A concave joint profile yields veneer with more water resistance (see Section 24.3).

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The backup wall in a brick veneer wall assembly consists of a
- **a.** reinforced-concrete wall.
- **b.** CMU wall.
- **c.** wood or steel stud wall.
- **d.** all of the above.
- **e.** (b) and (c) only.

2. In a brick veneer wall assembly, the wind loads are transferred directly from the veneer to the building's structure.
- **a.** True
- **b.** False

3. The anchors used to anchor the brick veneer to the backup wall are generally two-piece anchors to allow differential movement between the veneer and the backup
- **a.** in all three principal directions.
- **b.** perpendicular to the plane of the veneer.
- **c.** within the plane of the veneer.
- **d.** none of the above.

4. The anchors in a brick veneer wall assembly provide
- **a.** gravity load support to both veneer and backup.
- **b.** lateral load support to both veneer and backup.
- **c.** gravity load support to the veneer.
- **d.** lateral load support to the veneer.

5. The minimum required width of the air space between a brick veneer and a CMU backup wall is
- **a.** 1 in.
- **b.** $1\frac{1}{2}$ in.
- **c.** 2 in.
- **d.** 3 in.
- **e.** none of the above.

6. The minimum width of the air space generally used between a brick veneer and a wood stud backup wall is
- **a.** 1 in.
- **b.** $1\frac{1}{2}$ in.
- **c.** 2 in.
- **d.** $2\frac{1}{2}$ in.
- **e.** 3 in.

7. A steel angle used to support the weight of a brick veneer over an opening is called a
- **a.** lintel angle.
- **b.** shelf angle.
- **c.** relieving angle.
- **d.** all of the above.
- **e.** (a) or (b).

8. A shelf angle must be anchored to the building's structural frame.
- **a.** True
- **b.** False

9. A lintel angle must be anchored to the building's structural frame.
- **a.** True
- **b.** False

10. In a multistory building, shelf angles are typically used at
- **a.** each floor level.
- **b.** each floor level and at midheight between floors.
- **c.** at the foundation level.
- **d.** all of the above.
- **e.** (a) and (c).

11. For a brick veneer that bears on the foundation and continues to the top of the building without any intermediate bearing support, the maximum veneer height is limited to
- **a.** 40 ft.
- **b.** 35 ft.
- **c.** 30 ft.
- **d.** 25 ft.
- **e.** 20 ft.

12. A shelf angle in a brick veneer assembly must provide
- **a.** gravity load support to the veneer.
- **b.** lateral load support to the veneer.
- **c.** gravity load support to both veneer and backup.
- **d.** lateral load support to both veneer and backup.

13. In a brick veneer assembly, flashing is required
- **a.** at the foundation level.
- **b.** over a lintel angle.
- **c.** over a shelf angle.
- **d.** under a window sill.
- **e.** all of the above.

14. In a brick veneer assembly, weep holes are required at
- **a.** each floor level.
- **b.** each alternate floor level.
- **c.** immediately above the flashing.
- **d.** immediately below the flashing.
- **e.** 2 in. above a flashing.

15. The most efficient weep hole in a brick veneer consists of a
- **a.** wick.
- **b.** plastic tube.
- **c.** open-head joint.
- **d.** none of the above.

16. A mortar-capturing device in a brick veneer assembly is used
- **a.** at each floor level.
- **b.** at each alternate floor level.
- **c.** immediately above a flashing.
- **d.** immediately below a flashing.
- **e.** 2 in. above a flashing.

17. In a brick veneer assembly with punched windows, vertical expansion joints should be provided at a maximum distance of
- **a.** 40 ft in the field of the wall and 40 ft from a wall's corner.
- **b.** 30 ft in the field of the wall and 30 ft from a wall's corner.
- **c.** 30 ft in the field of the wall and 20 ft from a wall's corner.
- **d.** 20 ft in the field of the wall and 10 ft from a wall's corner.

28.2 BRICK VENEER WITH A CMU OR CONCRETE BACKUP WALL

Figure 28.17 shows an overall view of a brick veneer wall assembly with a CMU backup wall. The steel anchors that connect the veneer to the CMU backup wall are two-piece wire anchors. One piece of the anchor is part of the joint reinforcement embedded in the CMU walls, Figure 28.18(a).

Several other types of anchors used with a CMU backup wall are available. Figure 28.18(b) shows a typical anchor used with reinforced-concrete member (spandrel beam or backup wall).

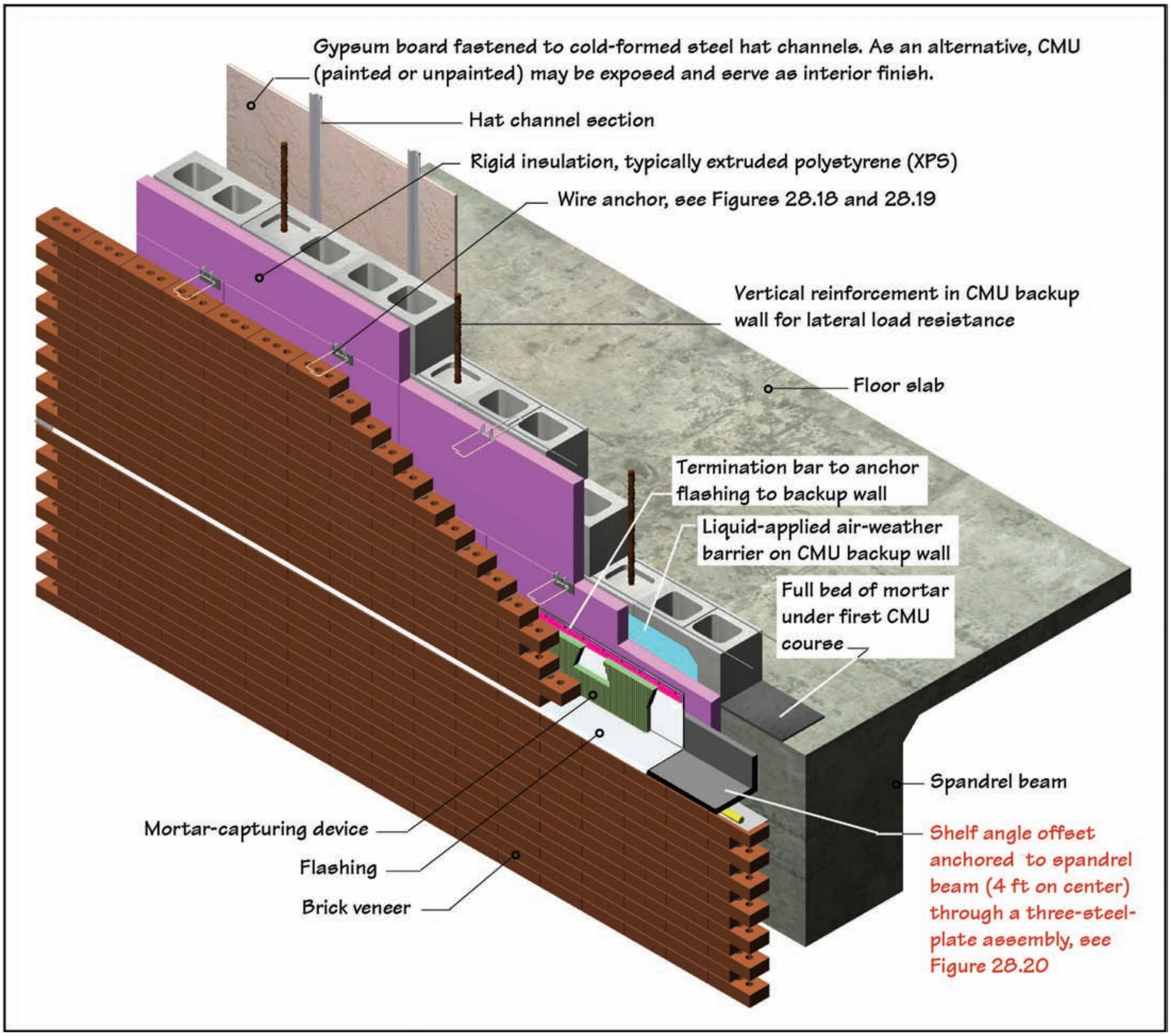
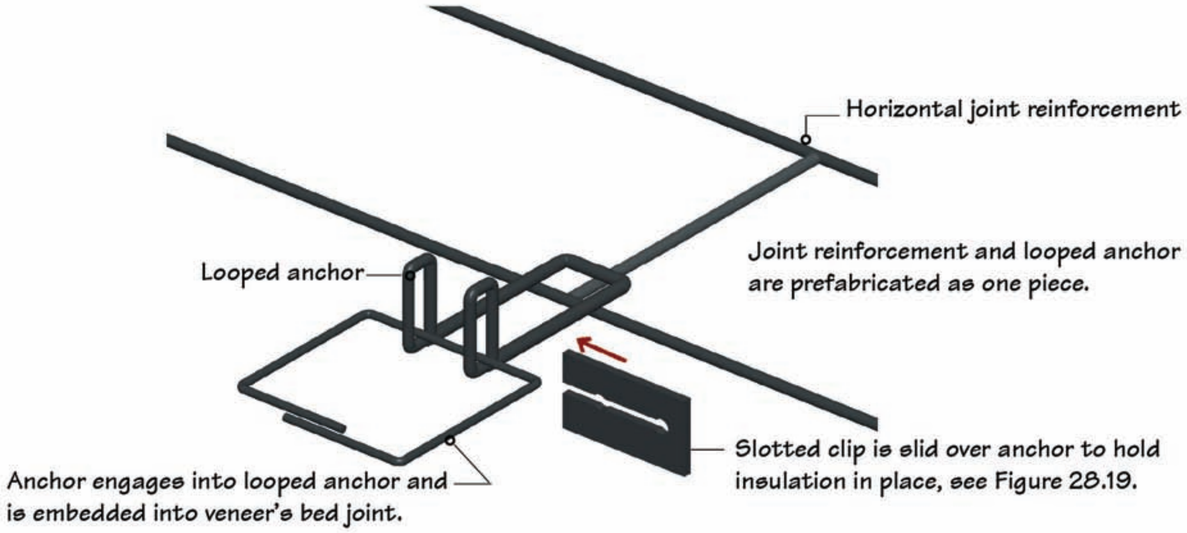
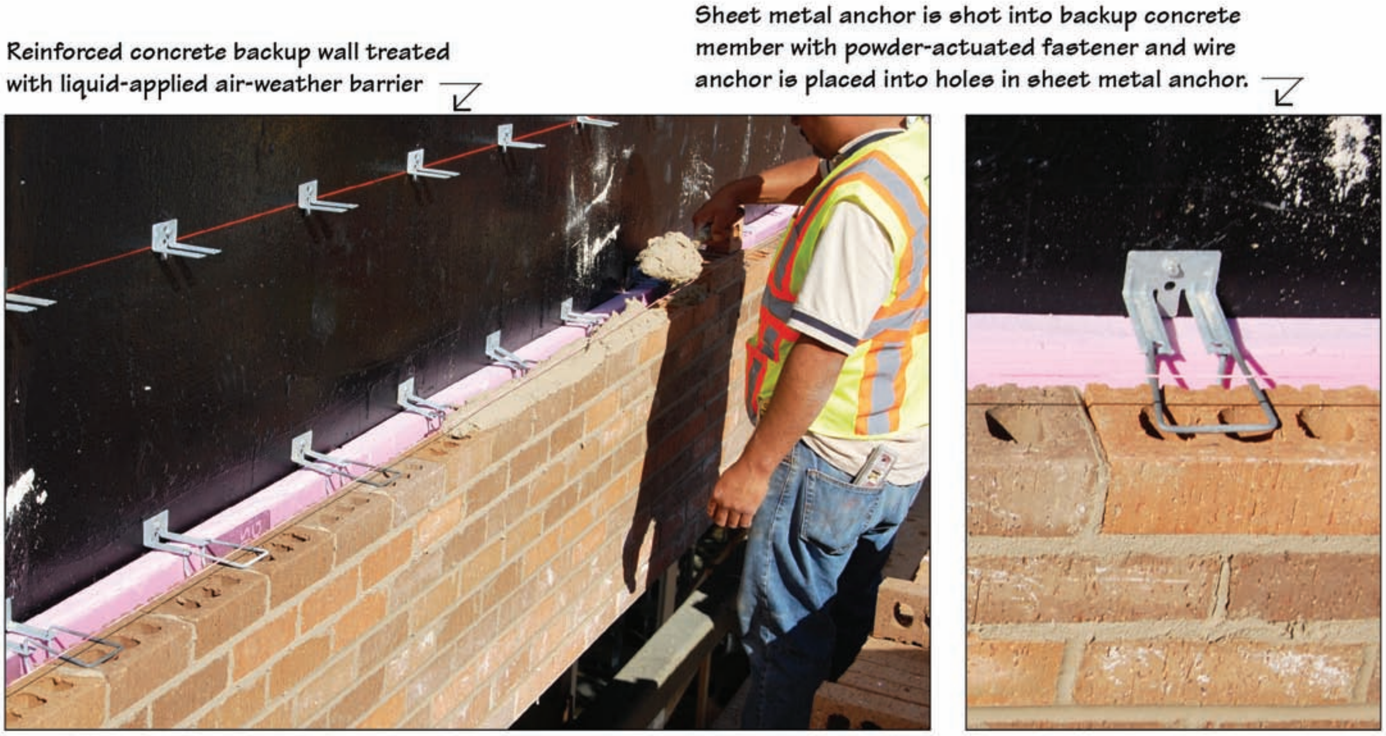

Gypsum board fastened to cold-formed steel hat channels. As an alternative, CMU (painted or unpainted) may be exposed and serve as interior finish.
Hat channel section
Rigid insulation, typically extruded polystyrene (XPS)
Wire anchor, see Figures 28.18 and 28.19
Vertical reinforcement in CMU backup wall for lateral load resistance
Floor slab
Termination bar to anchor flashing to backup wall
Liquid-applied air-weather barrier on CMU backup wall
Full bed of mortar under first CMU course
Spandrel beam
Shelf angle offset anchored to spandrel beam (4 ft on center) through a three-steel-plate assembly, see Figure 28.20
Mortar-capturing device
Flashing
Brick veneer

FIGURE 28.17 Brick veneer with CMU backup wall.


Horizontal joint reinforcement
Looped anchor
Joint reinforcement and looped anchor are prefabricated as one piece.
Slotted clip is slid over anchor to hold insulation in place, see Figure 28.19.
Anchor engages into looped anchor and is embedded into veneer's bed joint.

(a) A typical veneer anchor used with CMU backup walls


Reinforced concrete backup wall treated with liquid-applied air-weather barrier
Sheet metal anchor is shot into backup concrete member with powder-actuated fastener and wire anchor is placed into holes in sheet metal anchor.

(b) A typical two-piece anchor for connecting brick veneer to reinforced concrete backup (wall or beam) consisting of: (i) bent sheet metal and (ii) wire anchor that engages with sheet metal anchor

FIGURE 28.18 Typical anchors used with CMU and concrete backup walls. Note that because of the emphasis by the International Energy Conservation Code (IECC) on reducing (or eliminating) thermal bridges in the building envelope, manufacturers are developing fasteners with exposed parts encapsulated into plastics.

In seismic regions, the use of seismic clips is recommended. A seismic clip engages a continuous wire reinforcement in brick veneer. Both the seismic clip and the wire are embedded in the veneer's bed joint. A typical seismic clip is shown in Figure 28.19.

OFFSET ANCHORAGE OF SHELF ANGLE FOR CONTINUOUS INSULATION

Figure 28.20 shows the details of the anchorage of a shelf angle to a spandrel (reinforced concrete) beam with an offset—a space between the beam and the shelf angle. The offset allows the rigid insulation to cover the CMU backup wall and the beam continuously at the outside face except at locations of the anchorage assembly. If the shelf angle is anchored directly to spandrel beam, as shown in Figure 28.7(a), then the thermal bridge created by the shelf angle reduces the effective R-value of the exterior insulation substantially.

Whereas the offset anchors for shelf angle support in Figure 28.20 are specially fabricated for a project, that shown in Figure 28.21 is a standard product available from a manufacturer and can be used as an alternative to those shown in Figure 28.20. According to the anchor

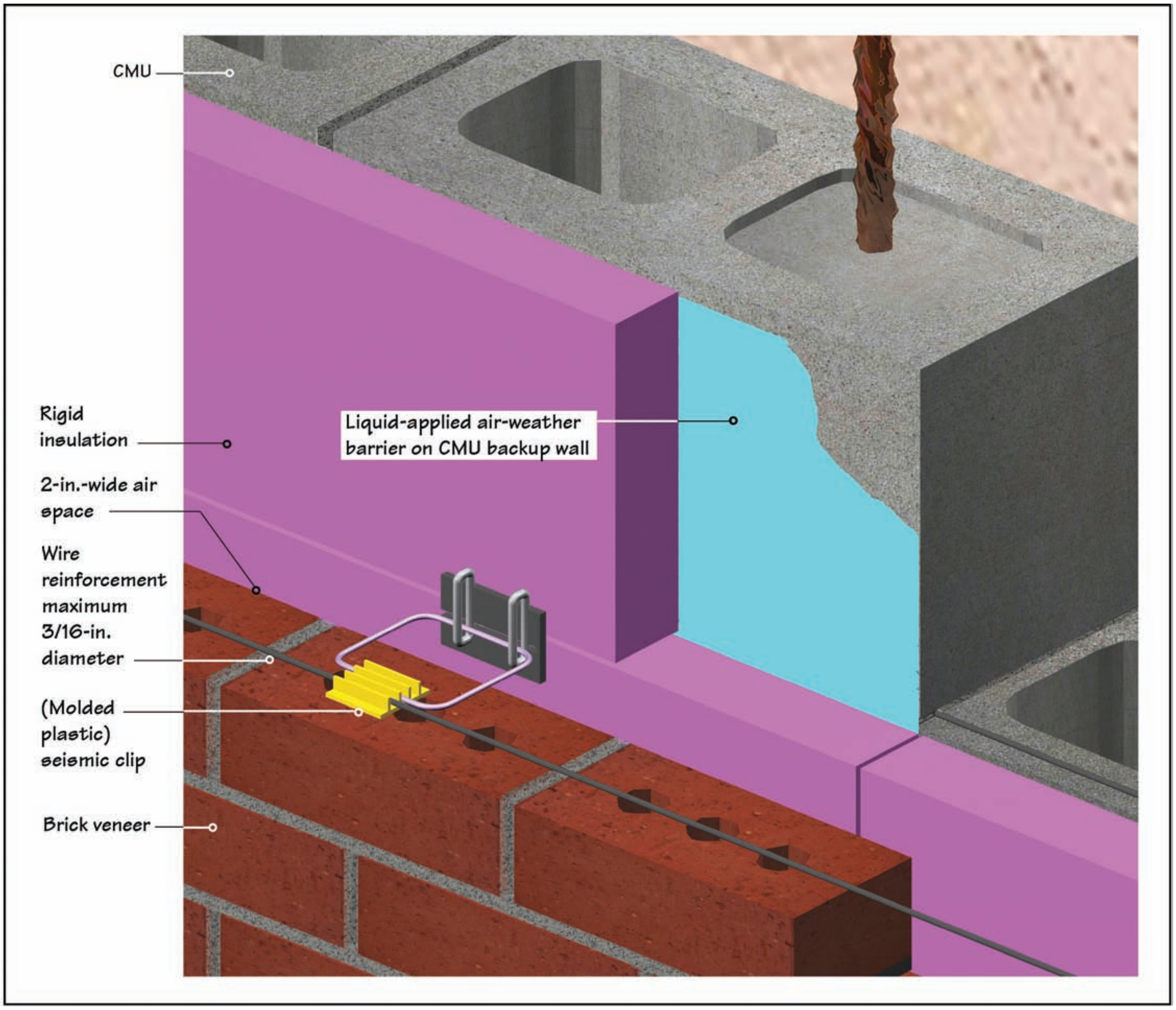
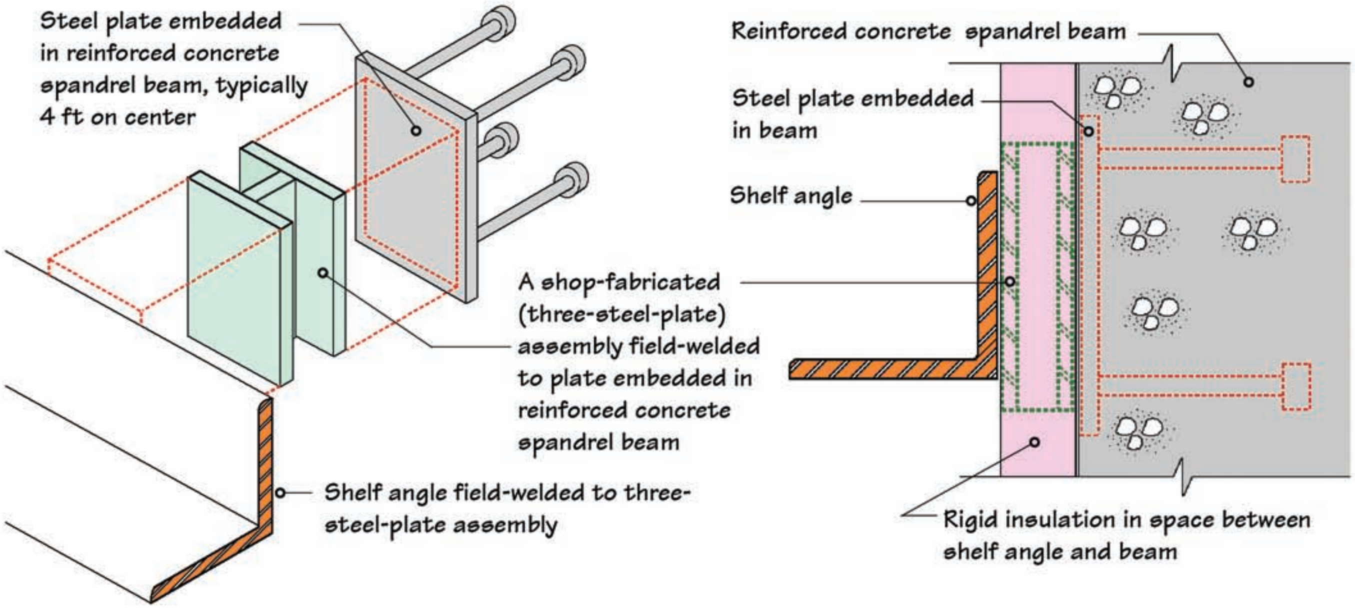
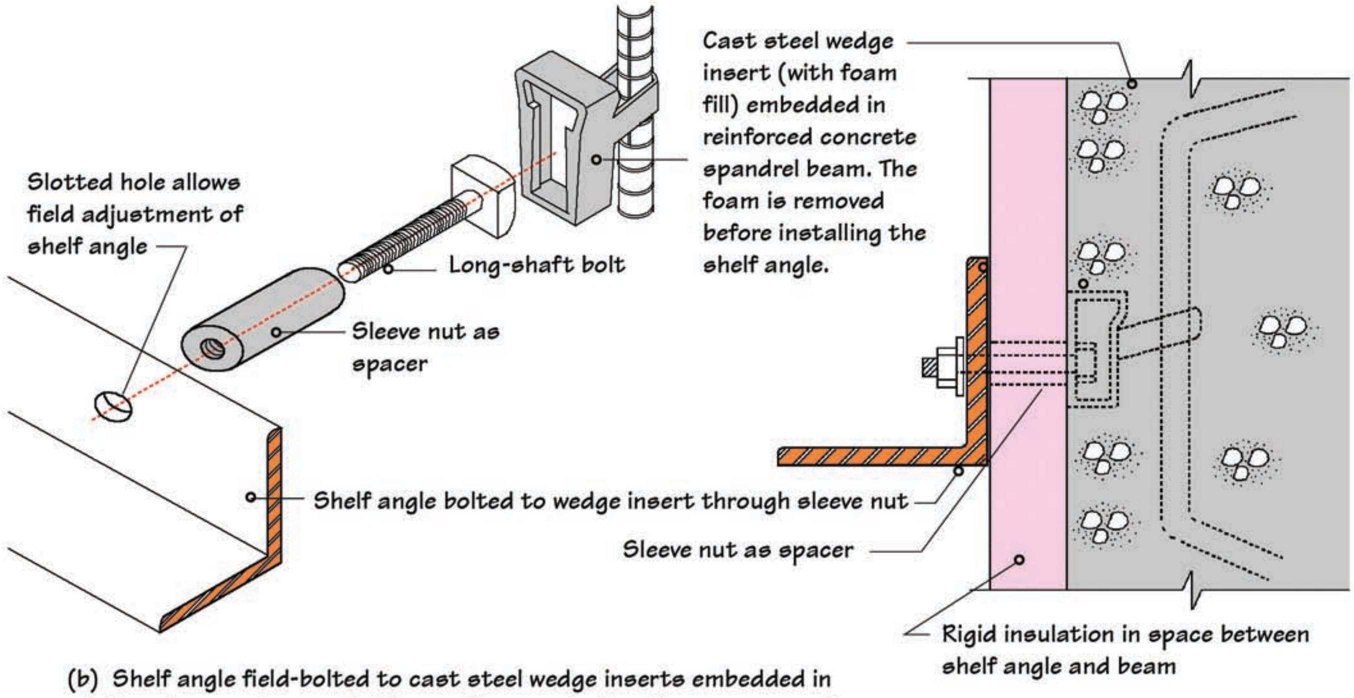

CMU
Rigid insulation
Liquid-applied air-weather barrier on CMU backup wall
2-in.-wide air space
Wire reinforcement maximum 3/16-in. diameter
(Molded plastic) seismic clip
Brick veneer

FIGURE 28.19 A typical seismic clip in brick veneer. The clip is embedded into mortar along with wire reinforcement.

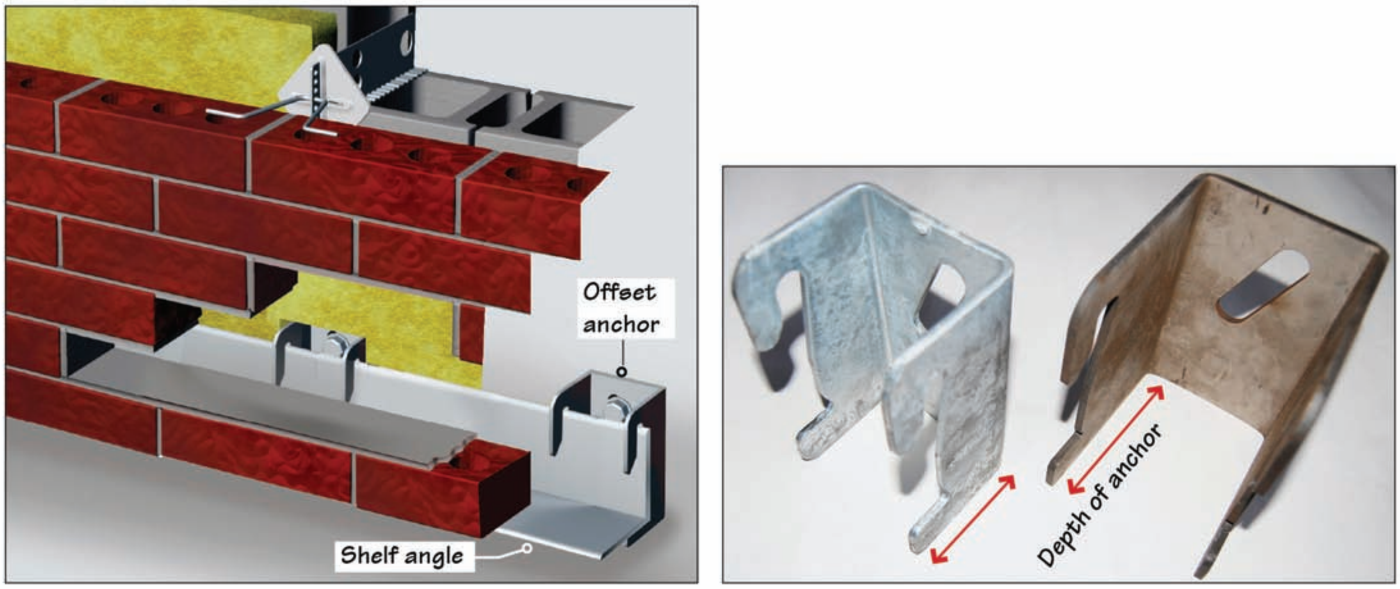

Steel plate embedded in reinforced concrete spandrel beam, typically 4 ft on center
A shop-fabricated (three-steel-plate) assembly field-welded to plate embedded in reinforced concrete spandrel beam
Shelf angle field-welded to three-steel-plate assembly
Reinforced concrete spandrel beam
Steel plate embedded in beam
Shelf angle
Rigid insulation in space between shelf angle and beam

(a) Offset anchorage of shelf angle to reinforced concrete spandrel beam using shop-fabricated (three-steel-plate) assemblies


Cast steel wedge insert (with foam fill) embedded in reinforced concrete spandrel beam. The foam is removed before installing the shelf angle.
Slotted hole allows field adjustment of shelf angle
Long-shaft bolt
Sleeve nut as spacer
Shelf angle bolted to wedge insert through sleeve nut
Sleeve nut as spacer
Rigid insulation in space between shelf angle and beam

(b) Shelf angle field-bolted to cast steel wedge inserts embedded in reinforced concrete spandrel beam. Sleeve nuts function as spacers to provide offset anchorage of shelf angle to beam.

FIGURE 28.20 Two alternative methods of anchoring a shelf angle to a reinforced-concrete spandrel beam. Method (a) is more commonly used. In this method, the shelf angles for all floors are in place before beginning the construction of the veneer. Method (b) allows the shelf angle to be installed after the veneer below the shelf angle has been constructed. This method is used where the veneer consists of large natural stone or cast-stone panels integrated with brick veneer, requiring a mechanical lifting device to bring the stone panels into position from the above. In such a situation, Method (a) cannot be used because the already installed shelf angles interfere with the placement of the stone panels.



(a) Offset anchor assembly

(b) Offset anchors available in different depths to match the thickness of continuous insulation

FIGURE 28.21 Offset anchor for shelf angle support available as standard product. Illustration (a) courtesy of Fero Corporation.

manufacturer, it reduces the time and cost of shelf angle installation. Because fastening these anchors and installing the shelf angles does not require welding, it can be done by the masons, eliminating the welding trade and hence speeding the construction.

The width of the offset space is a function of the required R-value and the type of exterior insulation. For example, if the R-value required of exterior insulation is R-10, then a 2-in.-thick extruded polystyrene (XPS) insulation can be used because R-value of 1-in.-thick XPS is 5.0, see Table 5.2.

As stated in Section 27.4, if the building is modeled for energy use in terms of whole building performance, then the prescriptive requirements of the International Energy Conservation Code (IECC) for the use of continuous insulation may be ignored. In that case, the shelf angle may be anchored directly to spandrel beam. However, offset anchorage of shelf angle is still preferable because of reduced energy use.

ADDITIONAL DETAILS OF BRICK VENEER WITH CMU BACKUP WALL

Figure 28.22(a) shows a wall section of a typical CMU-backed brick veneer cladding with continuous insulation and Figure 28.22(b) zooms in on a part of this section. Note that whereas the CMU backup wall is anchored to the spandrel beam at the floor level, it has a gap under the spandrel beam to allow for an unrestrained deflection of the beam. This ensures that the backup wall is not subjected to any gravity load other than its self load. However, the wall must be able to resist lateral loads. Two alternative details for lateral load support of CMU backup wall are shown in Figure 28.23. Figure 28.23(a) shows the use of clip angles anchored to the underside of the beam at approximately 4 ft on center.

In Figure 28.23(b), an anchor comprising a steel bar with a flattened, dovetail top is used in the recess of every CMU sash unit. The recess is filled with mortar after the anchor's installation. The cylindrical part of the anchor is covered with a plastic tube, which functions as a bond breaker between the anchor and the mortar to allow the beam to deflect freely.

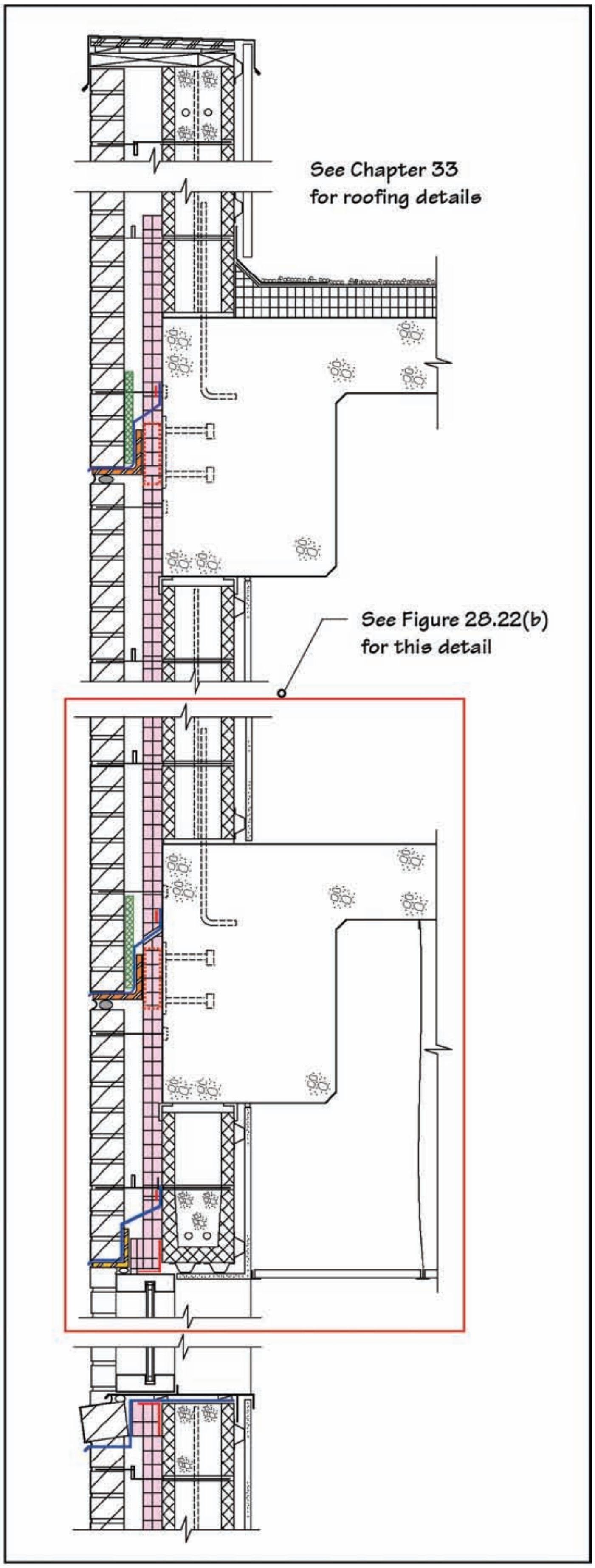

See Chapter 33
for roofing details
See Figure 28.22(b)
for this detail

FIGURE 28.22(a) Wall section through typical multistory reinforced-concrete frame building with brick veneer and CMU backup wall.

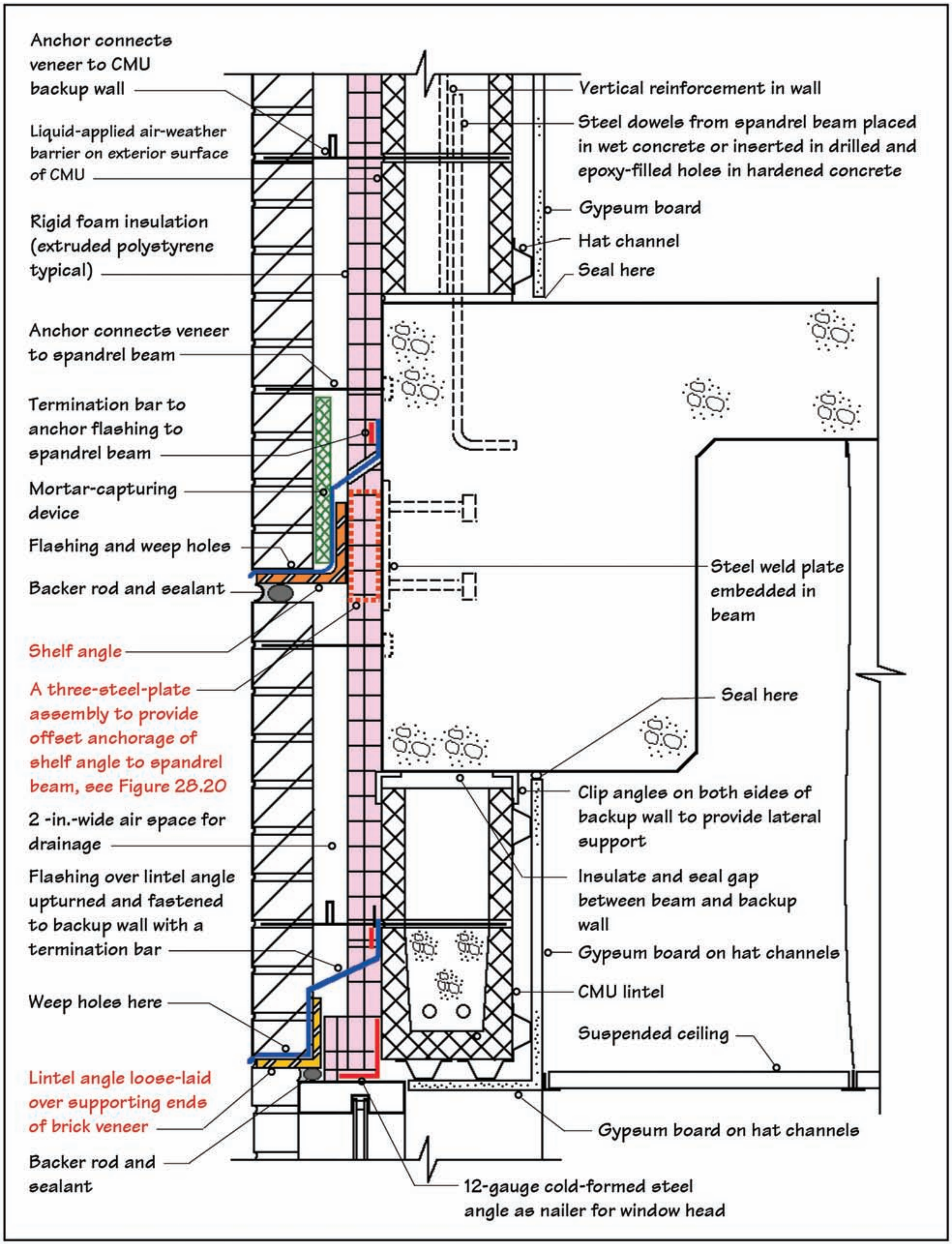
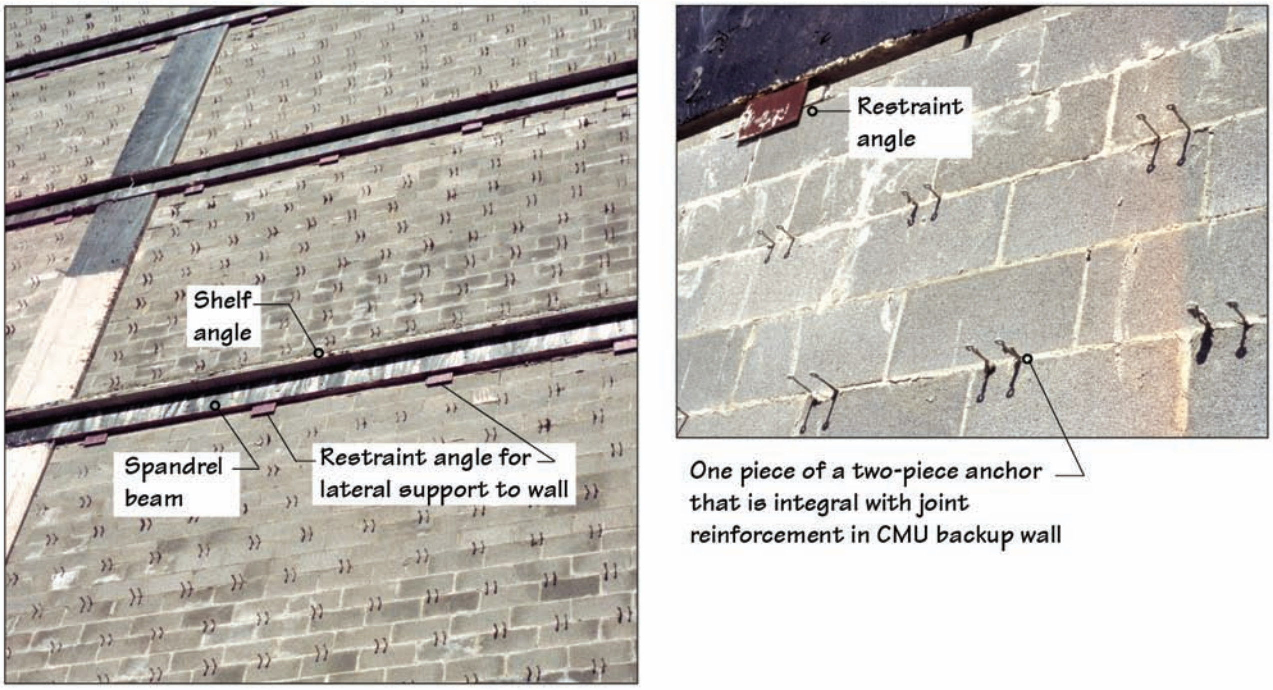
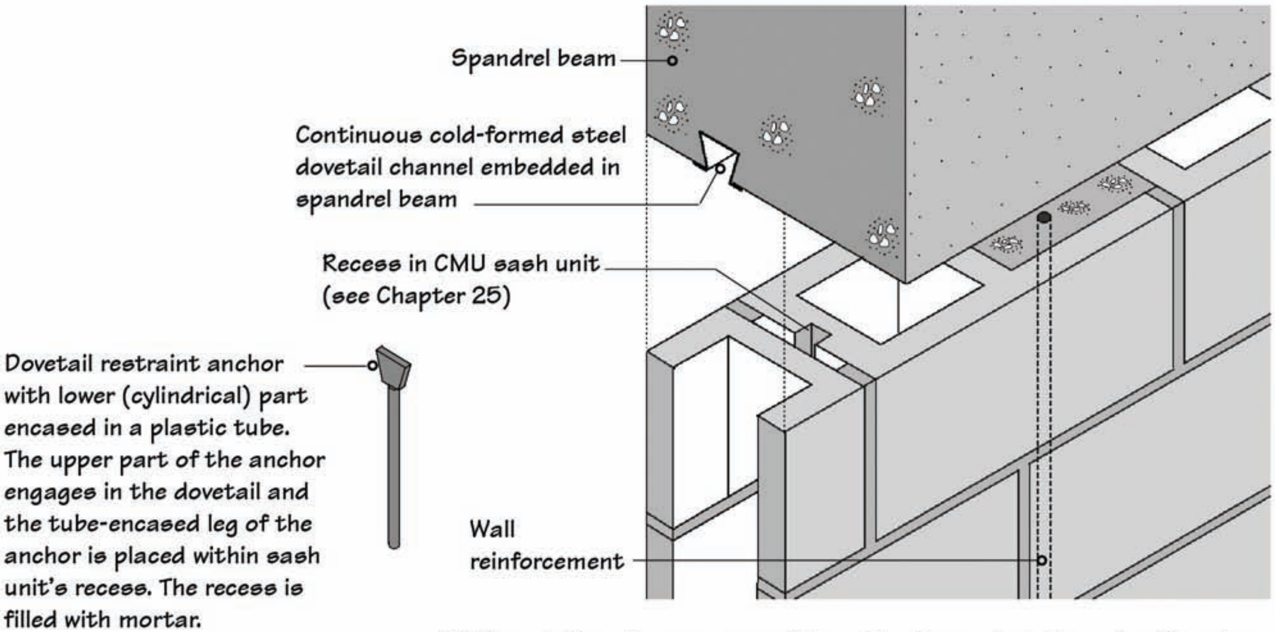

Anchor connects veneer to CMU backup wall
Liquid-applied air-weather barrier on exterior surface of CMU
Rigid foam insulation (extruded polystyrene typical)
Anchor connects veneer to spandrel beam
Termination bar to anchor flashing to spandrel beam
Mortar-capturing device
Flashing and weep holes
Backer rod and sealant
Shelf angle
A three-steel-plate assembly to provide offset anchorage of shelf angle to spandrel beam, see Figure 28.20
2 -in.-wide air space for drainage
Flashing over lintel angle upturned and fastened to backup wall with a termination bar
Weep holes here
Lintel angle loose-laid over supporting ends of brick veneer
Backer rod and sealant
Vertical reinforcement in wall
Steel dowels from spandrel beam placed in wet concrete or inserted in drilled and epoxy-filled holes in hardened concrete
Gypsum board
Hat channel
Seal here
Steel weld plate embedded in beam
Seal here
Clip angles on both sides of backup wall to provide lateral support
Insulate and seal gap between beam and backup wall
Gypsum board on hat channels
CMU lintel
Suspended ceiling
Gypsum board on hat channels
12-gauge cold-formed steel angle as nailer for window head

FIGURE 28.22(b) Refers to Figure 28.22(a).


Shelf angle
Spandrel beam
Restraint angle for lateral support to wall
Restraint angle
One piece of a two-piece anchor that is integral with joint reinforcement in CMU backup wall

(a) Restraint angles are attached to the bottom of the spandrel beam. Spacing of restraint angles is a function of lateral load on wall.


Spandrel beam
Continuous cold-formed steel dovetail channel embedded in spandrel beam
Recess in CMU sash unit (see Chapter 25)
Dovetail restraint anchor with lower (cylindrical) part encased in a plastic tube. The upper part of the anchor engages in the dovetail and the tube-encased leg of the anchor is placed within sash unit's recess. The recess is filled with mortar.
Wall reinforcement

(b) Dovetail anchors are an alternative to restraint angles. Spacing of anchors is a function of lateral load on wall.

FIGURE 28.23 Two alternative methods of providing lateral load restraint at the top of a CMU backup wall.

The shelf angle and the lintel angle can be combined into one angle by increasing the depth of the spandrel beam so that it is in line with the level of the window head, Figure 28.24. This strategy is commonly used with ribbon windows and continuous brick veneer spandrels, Figure 28.25.

AIR AND WATER RESISTANCE OF CMU BACKUP WALL

It is important that the exterior face of the CMU backup wall is treated to resist air leakage and bulk water. Several proprietary liquid-applied air-weather barriers are available for the purpose, which are either rolled, mopped, or sprayed on the wall (see Figure 6.11).

28.3 BRICK VENEER WITH A STEEL STUD BACKUP WALL

The construction of brick veneer with a steel stud backup wall differs from that of a CMU-backed wall mainly in the anchors used for connecting the veneer to the backup. Various types of anchors are available to suit different conditions. The anchor shown in Figure 28.26 is used where rigid insulation is applied to the outside of the backup wall (which is generally the case because of thermal bridging issues). The sharp ends of the prong-type anchor pierce the insulation up to the sheathing and transfer the lateral load to the studs without compressing the insulation. Note that the prongs do not pierce the sheathing.

STEEL STUD–BACKED BRICK VENEER WALL IN MULTISTORY STEEL AND CONCRETE FRAME STRUCTURES

Figure 28.27 shows a detailed section of brick veneer with a steel stud backup wall in a reinforced-concrete structural frame. The (vertical) deflection of the spandrel beam is accommodated for by providing a two-track assembly consisting of two nested deep-leg tracks. The upper track of this slip assembly is fastened to the beam. The studs and the interior

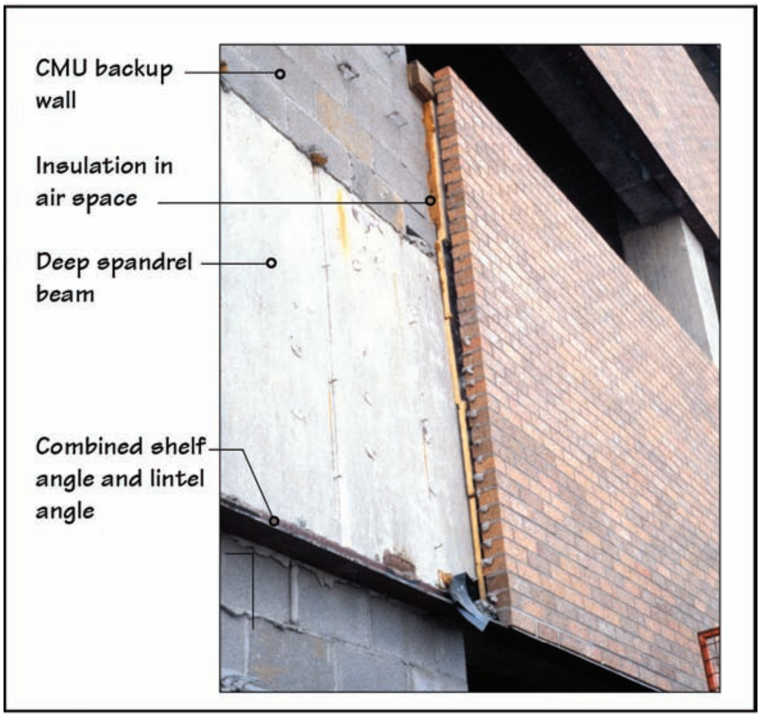


FIGURE 28.24 With a deep spandrel beam, which extends from the window head in the lower floor to the level of the upper floor, the shelf angle and lintel angle are combined into one angle.

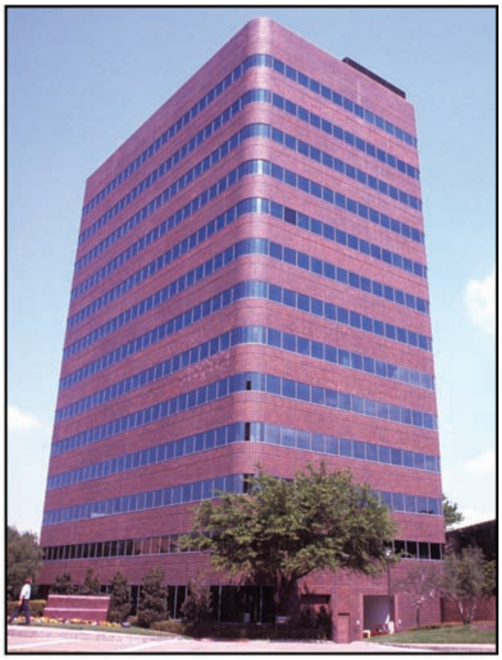
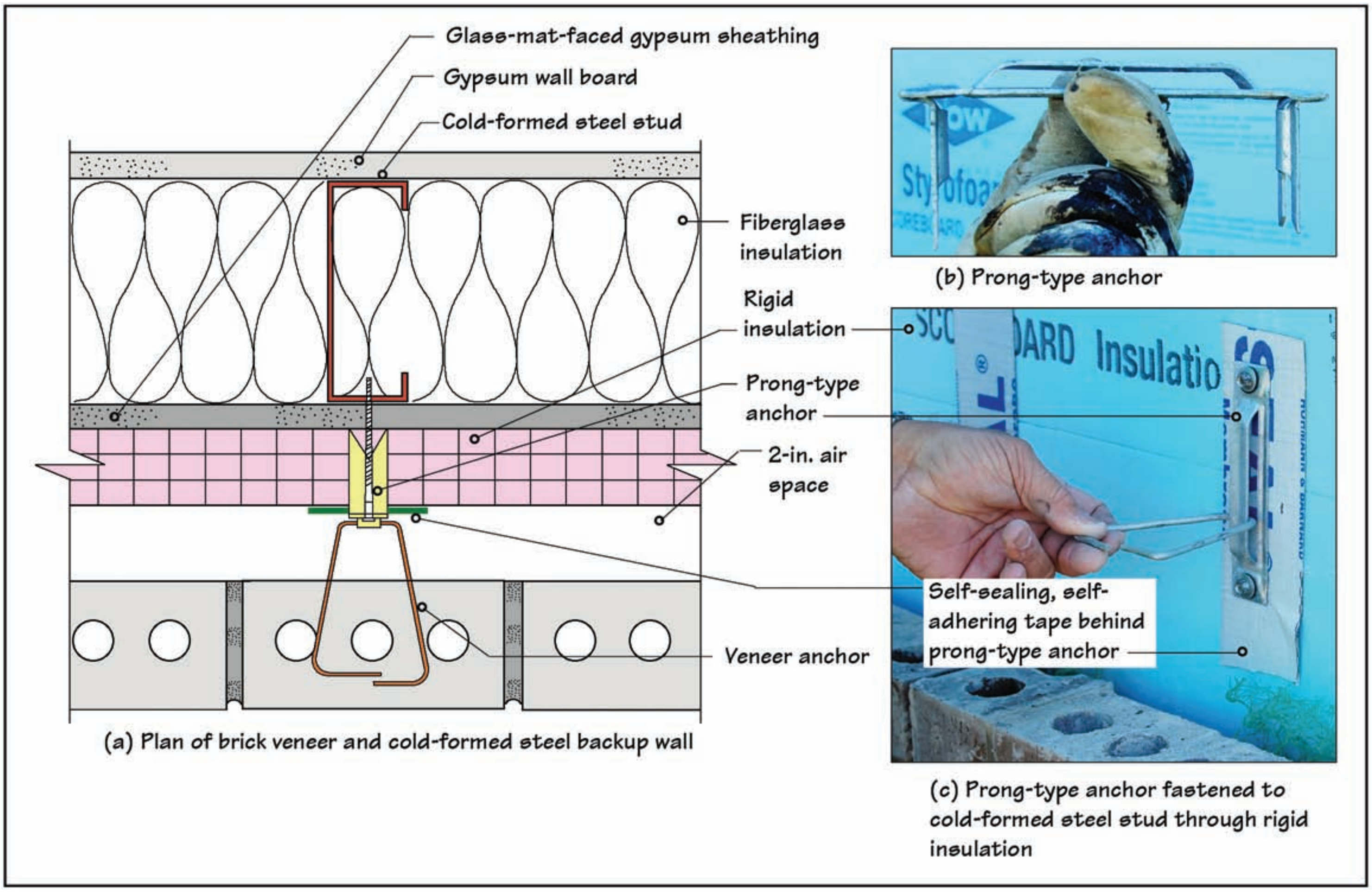


FIGURE 28.25 A building with brick veneer spandrels and ribbon windows.


Glass-mat-faced gypsum sheathing
Gypsum wall board
Cold-formed steel stud
Fiberglass insulation
Rigid insulation
Prong-type anchor
2-in. air space
Veneer anchor
Self-sealing, self-adhering tape behind prong-type anchor

(a) Plan of brick veneer and cold-formed steel backup wall

(b) Prong-type anchor

(c) Prong-type anchor fastened to cold-formed steel stud through rigid insulation

FIGURE 28.26 A typical steel stud and brick veneer assembly with continuous rigid insulation outside exterior sheathing. Flexible insulation is placed between studs as needed. The prong-type anchor is hammered through rigid insulation and fastened to the stud.

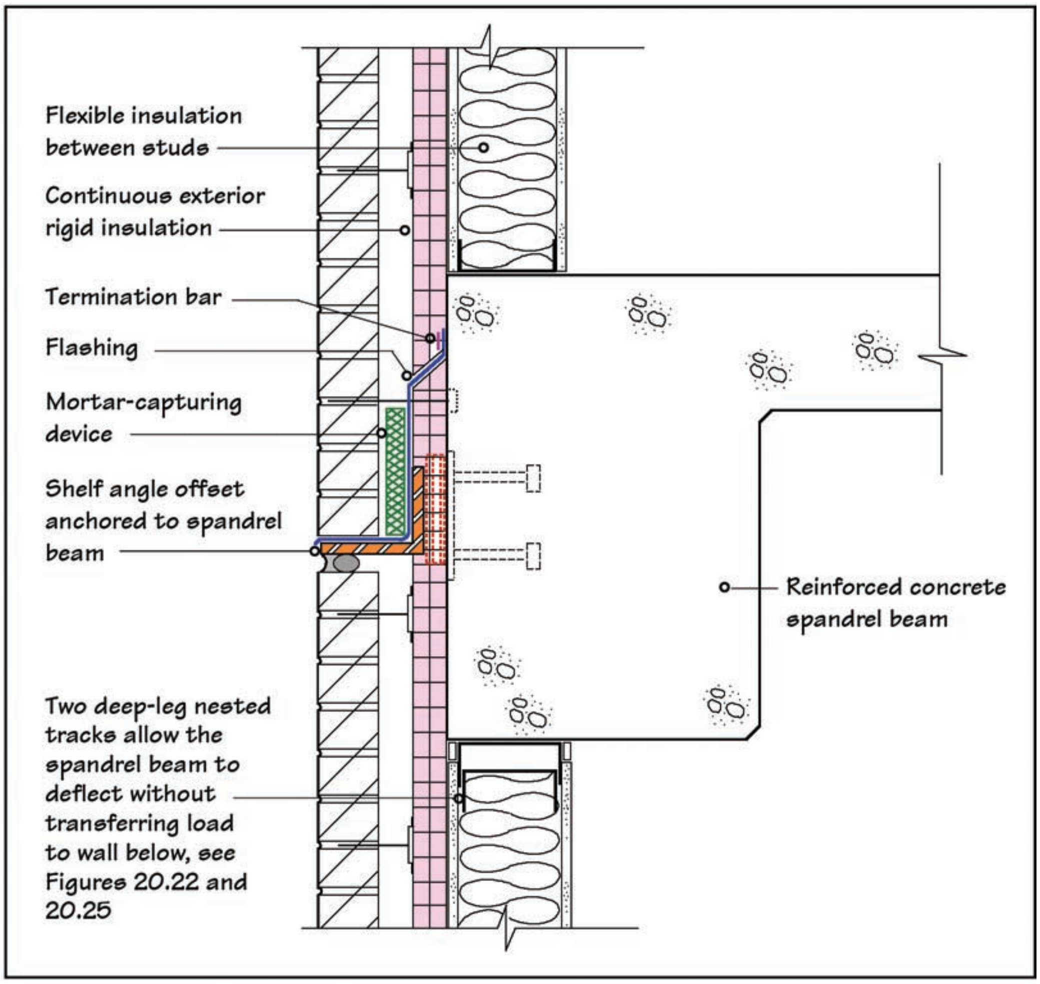

Flexible insulation between studs
Continuous exterior rigid insulation
Termination bar
Flashing
Mortar-capturing device
Shelf angle offset anchored to spandrel beam
Two deep-leg nested tracks allow the spandrel beam to deflect without transferring load to wall below, see Figures 20.22 and 20.25
Reinforced concrete spandrel beam

FIGURE 28.27 Detail at floor level of typical brick veneer cladding backed by cold-formed steel stud assembly in a reinforced-concrete frame structure.

drywall are fastened only to the lower track, which allows the upper track to slide over the lower track (see Chapter 20). Figure 28.28 shows a detail section through a steel stud–backed brick veneer cladding in a steel-frame building.

BRICK VENEER AND STEEL STUD BACKUP WALL IN LOW-RISE BUILDINGS

In low-rise buildings (one or two stories), placing the steel stud backup wall on the outside of the structure allows it to cover the structural frame. Thus, the studs are continuous from the bottom to the top, requiring no shelf angles, Figures 28.29 and 28.30. Slip connections

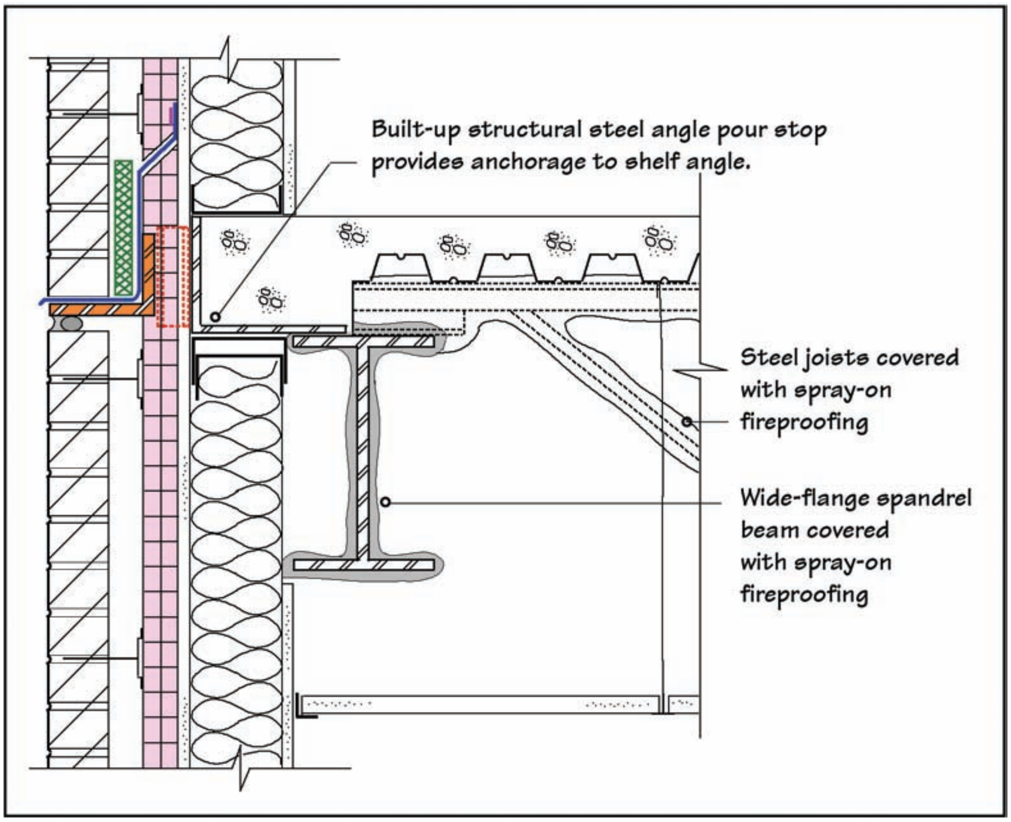

Built-up structural steel angle pour stop provides anchorage to shelf angle.
Steel joists covered with spray-on fireproofing
Wide-flange spandrel beam covered with spray-on fireproofing

FIGURE 28.28 Detail at floor level of typical brick veneer cladding backed by cold-formed steel stud assembly in a steel-frame structure. For several items not labeled in this illustration, see Figure 28.27.

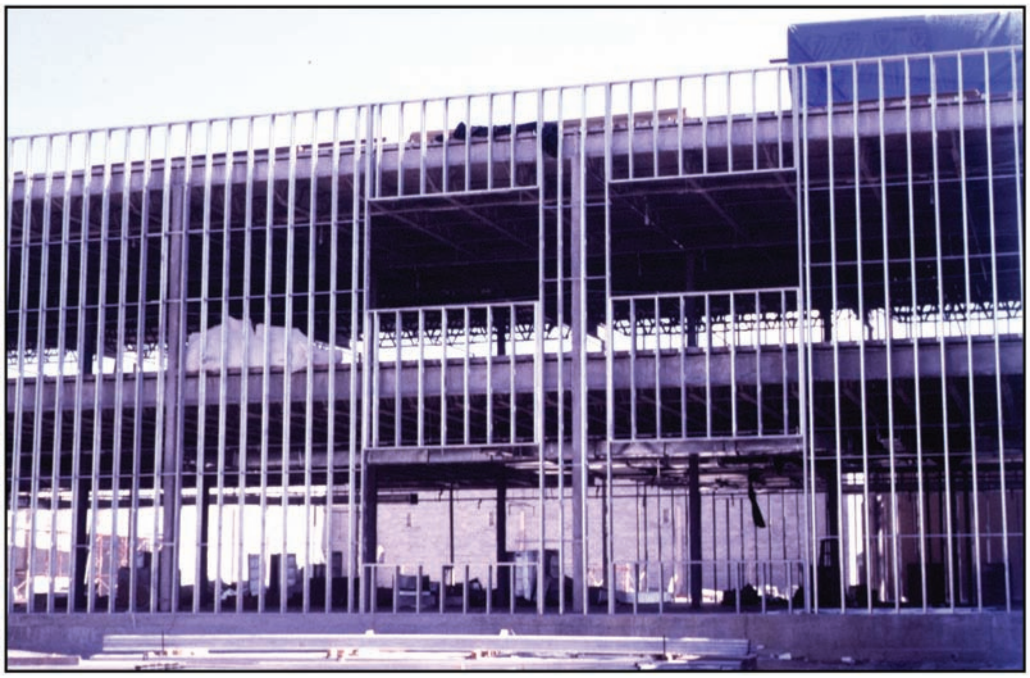


FIGURE 28.29 In a one- or two-story building with cold-formed steel (CFS) stud backup wall, the studs are generally continuous from the foundation to the roof, requiring no shelf angle supports. The vertical continuity of studs across a floor and/or roof increases their lateral load resistance. Refer to Figure 28.30 for details.

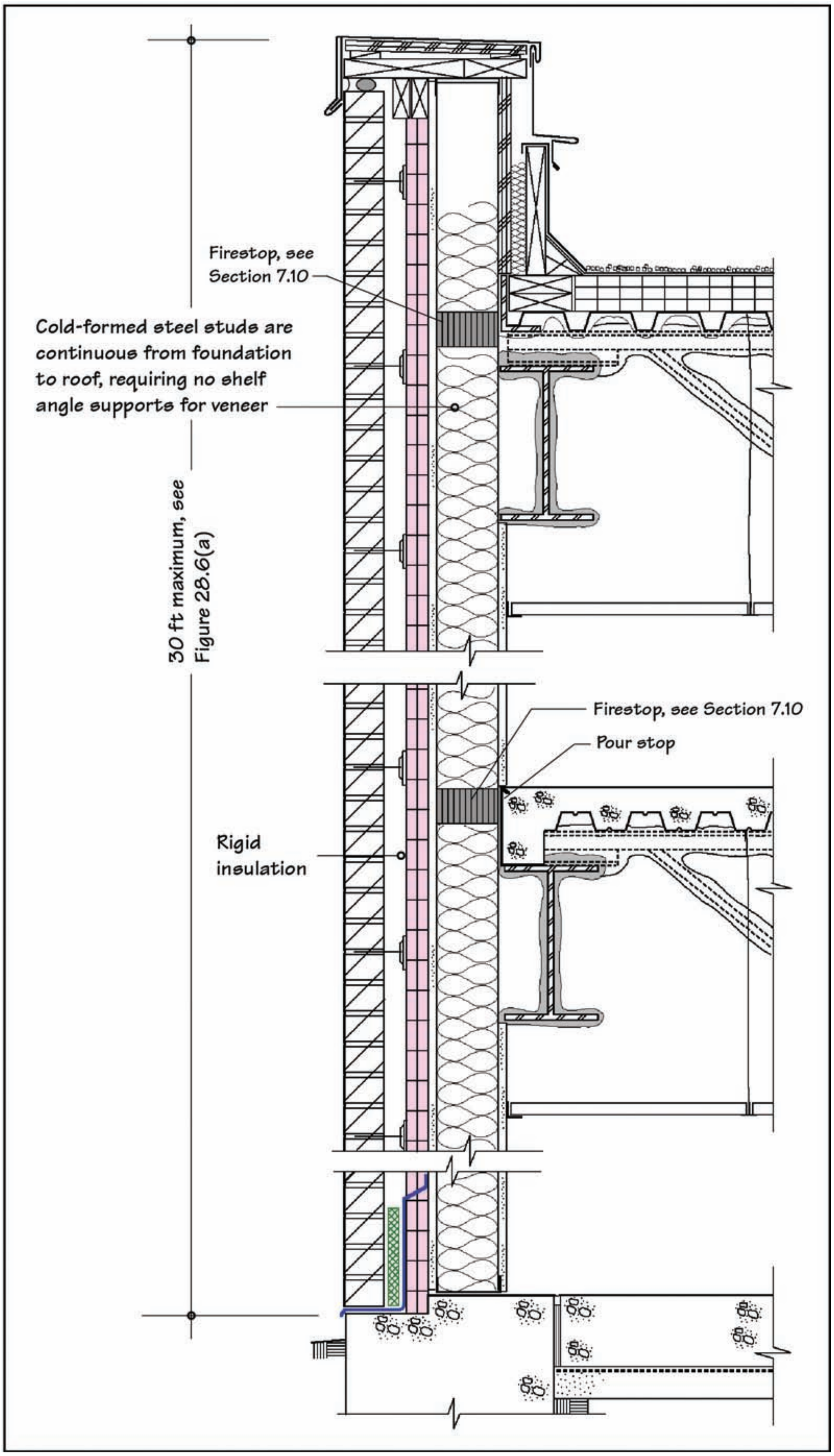

Firestop, see
Section 7.10
Cold-formed steel studs are
continuous from foundation
to roof, requiring no shelf
angle supports for veneer
30 ft maximum, see
Figure 28.6(a)
Firestop, see Section 7.10
Pour stop
Rigid
insulation

FIGURE 28.30 A typical section through a low-rise (one- or two-story) building with a brick veneer and steel stud backup wall assembly. Steel studs in backup framing are continuous from the foundation to the roof. This assembly does not require shelf angles.

must be used to connect the studs with the floor or roof so that the structural frame and the wall can move independently of each other (see Figure 20.24).

AIR-WEATHER RESISTANCE OF A STEEL STUD BACKUP WALL

An air-weather barrier is required on exterior sheathing in steel stud walls and may be accomplished by using either (a) a wrap-type air-weather retarder or (b) a liquid-applied air-weather retarder. The latter alternative is more commonly used for commercial buildings.

28.4 CMU BACKUP VERSUS STEEL STUD BACKUP

A major benefit of a steel stud backup wall in a brick veneer assembly (compared with a CMU backup wall) is its lighter weight. For a high-rise building, the lighter wall reduces the size of not only spandrel beams but also columns and footings, yielding economy in the building's structure. However, this benefit is accompanied by several concerns.

Steel studs can deflect considerably before the bending stress in them exceeds their ultimate capacity. Brick veneer, on the other hand, deflects by a very small amount before the mortar joints open. Open mortar joints weaken the wall and increase the probability of leakage, corroding the anchors.

Thus, the steel stud backup and brick veneer assembly performs well only if the stud wall is sufficiently stiff. To obtain the necessary stiffness, the deflection of studs must be controlled to a fairly small value. In fact, the design of a steel stud backup wall to resist the lateral loads is governed not by the strength of studs but by their deflection.

The Brick Industry Association (BIA) recommends that the lateral load deflection of steel studs, when used as backup for brick veneer assembly, should not exceed

$$\frac{\text{stud span}}{600}$$

where the stud span is the unsupported height of studs. For example, if the height of studs (e.g., from the top of the floor to the bottom of the spandrel beam in Figure 28.7) is 10 ft, the deflection of studs under the lateral load must be less than

$$\frac{(10 \times 12)}{600} = 0.5 \text{ in.}$$

Increasing the stiffness of studs increases the cost of the assembly. Another concern with steel stud backup is that the veneer is anchored to the backup only through screws that engage the threads within a cold-formed stud sheet. Over a period of time, condensation can corrode the screws and the corresponding holes in studs, causing the screws to come loose. Condensation is, therefore, an important concern in a steel stud–backed veneer. A more serious concern is that the anchor installer will miss the studs.

By comparison with steel studs, anchoring of brick veneer to a CMU backup wall does not depend on screws; hence, it is more forgiving. Additionally, the anchors in a CMU backup wall are embedded in the mortar joints, and if they are made of stainless steel, their corrosion probability is extremely low.

Another advantage of a CMU backup wall is its inherent stiffness. Obtaining a steel stud backup wall of the same stiffness as a CMU backup wall substantially increases the cost of the stud backup.

NOTE

Deflection of a Steel Stud Wall Assembly

The design criterion of deflection not exceeding span divided by 600, suggested by BIA, is the minimum requirement. For critical buildings, a more stringent deflection criterion, such as span divided by 720 or span divided by 900, is recommended by some experts.

Steel stud manufacturers generally provide tables for the selection of their studs to conform to the deflection criteria.

28.5 AESTHETICS OF BRICK VENEER

It is neither possible nor within the scope of this text to illustrate the various techniques used to add visual interest to brick veneer facades. However, a few examples are provided:

- Using recessed or projected bricks in the wall, Figure 28.31(a).
- Using bricks of different colors or combining clay bricks with other masonry materials or cast concrete, Figure 28.31(b).

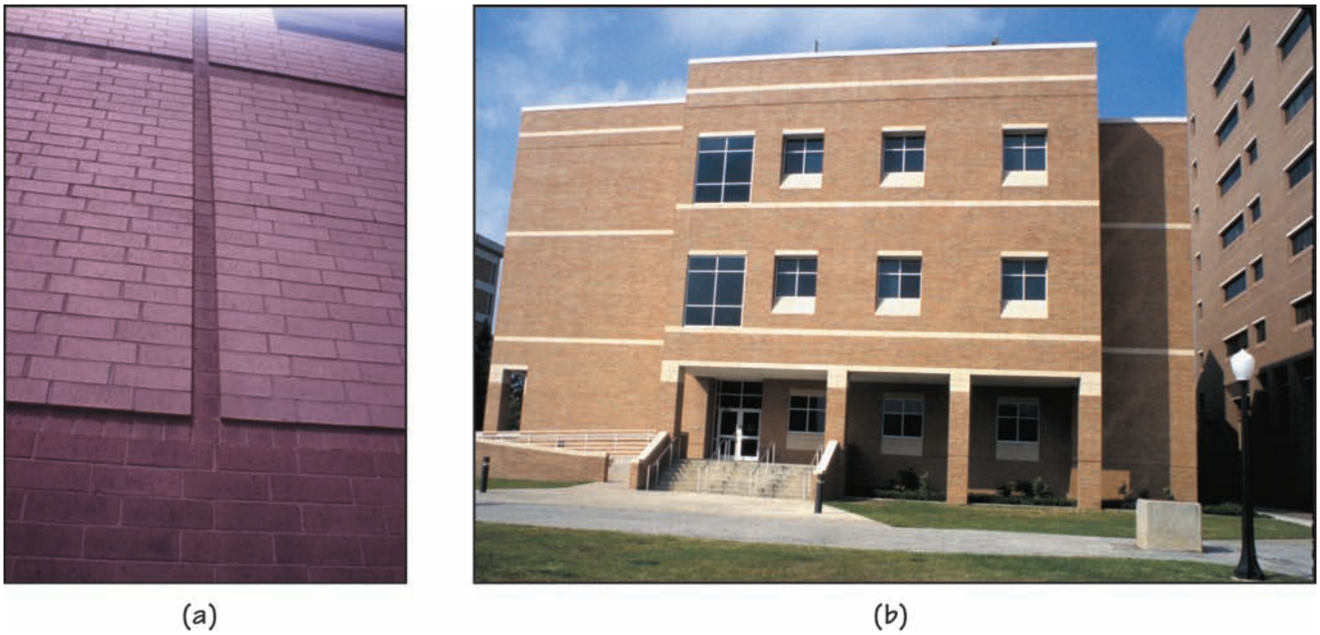


FIGURE 28.31 **(a)** Use of recessed or projected bricks with different hues. The projections must be small so that the core holes in bricks are not exposed. **(b)** Precast (white) concrete members (of the same thickness as bricks) used as bands in veneer.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

18. A typical anchor used with a brick veneer and CMU backup wall assembly consists of a
- **a.** two-piece anchor, of which one is embedded in the CMU backup wall and the other is embedded in the veneer's mortar joint.
- **b.** three-piece anchor, of which two are fastened to the CMU backup wall and the other is embedded in the veneer's mortar joint.
- **c.** two-piece anchor, of which one is an integral part of the joint reinforcement in the CMU backup wall and the other is embedded in the veneer's mortar joint.
- **d.** (a) and (b).
- **e.** (a) and (c).

19. When lintel angles and shelf angles are combined in the same angle in a brick veneer–clad building, the angle should be treated as a
- **a.** lintel angle anchored to the structural frame of the building.
- **b.** lintel angle loose-laid over underlying veneer.
- **c.** shelf angle loose-laid over underlying veneer.
- **d.** shelf angle anchored to the structural frame of the building.

20. In general, a CMU-backed brick veneer is more forgiving of construction and workmanship deficiencies than a steel stud–backed brick veneer.
- **a.** True
- **b.** False

21. In a brick veneer assembly with a steel stud backup wall, the design of studs is generally governed by
- **a.** the compressive strength of studs to withstand gravity loads.
- **b.** the shortening of studs to withstand gravity loads.
- **c.** the bending strength of studs to withstand lateral loads.
- **d.** the deflection of studs to withstand lateral loads.
- **e.** any one of the above, depending on the wall.

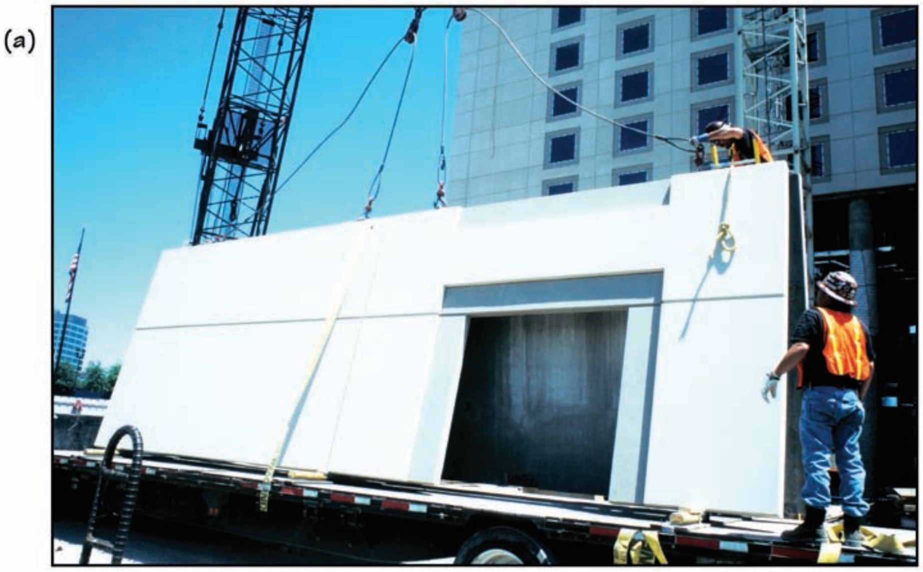
28.6 PRECAST CONCRETE (PC) CURTAIN WALL

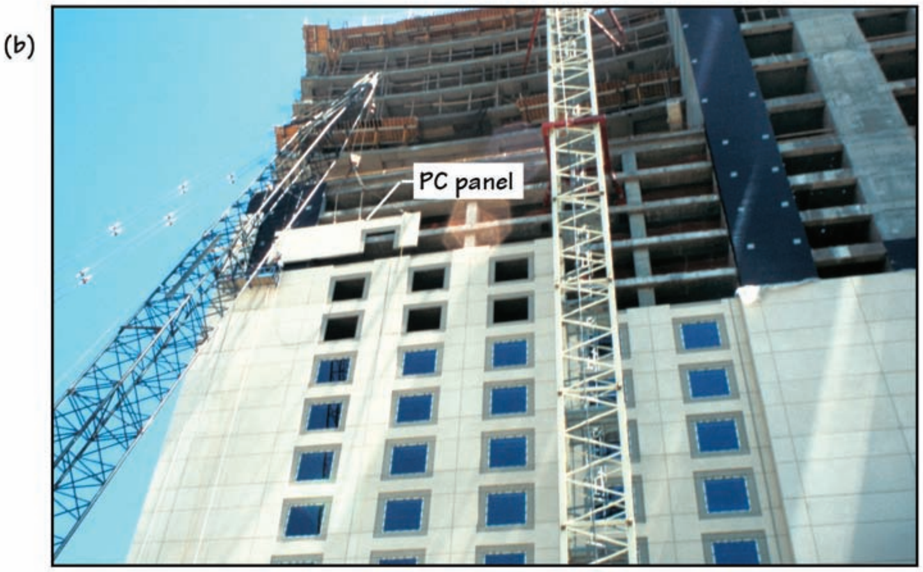
Unlike brick veneer, which is constructed brick by brick at the construction site, a precast concrete (PC) curtain wall is panelized construction. The panels are constructed off-site, under controlled conditions, and transported to the site in ready-to-erect condition, greatly reducing on-site construction time.

Although the PC curtain wall system is used in all climates, it is particularly favored in harsh climates, where on-site masonry and concrete construction are problematic due to the freeze hazard and the slow curing rate of Portland cement. Panelized construction eliminates scaffolding, increasing on-site workers' safety. Because panel fabrication can be done in sheltered areas, it can be accomplished uninterrupted, with a higher degree of quality control.

PC curtain walls are used for almost all building types but more often are used for mid to high-rise hospitals, apartment buildings, hotels, parking garages, and office buildings, Figure 28.32.

PC curtain wall panels are supported on and anchored to the building's structural frame and are hoisted in position by cranes, Figures 28.33(a) and (b). The panels are fabricated in a precast concrete plant and transported to the construction site.





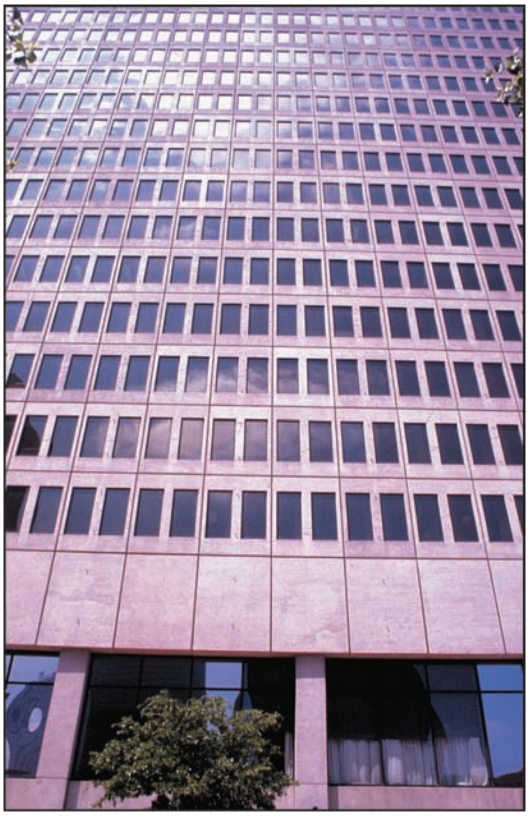


FIGURE 28.32 A typical office building with precast concrete curtain wall panels.

FIGURE 28.33 **(a)** A precast concrete panel being unloaded from the delivery truck for hoisting into position by a crane. **(b)** The same panel being hoisted into its final position.

NOTE

Architectural Precast and Structural Precast

In the building industry, precast concrete curtain walls are referred to as *architectural precast* concrete members, which distinguishes them from *structural precast* concrete members such as double tees, hollow-core slabs, and so on, covered in Chapter 23. Generally, the precasting companies fabricate either architectural precast or structural precast members.

The structural design of PC curtain wall panels is generally done by the panel fabricator to suit the fabrication plant's setup and resources and to provide an economical product. A typical precast concrete plant generally has in-house structural engineering expertise.

In a PC curtain wall project, an important role for the architect is to work out the aesthetic expression of the panels (shapes, size, exterior finishes, etc.). This should be done in consultation with the precast plant. A great deal of coordination between the architect, engineer of record, general contractor, precast plant, and erection subcontractor is necessary for a successful PC curtain wall project.

Because of the sculptability of concrete and the assortment of possible finishes of the concrete surface (smooth, abrasive-blasted, acid-etched, etc.), PC curtain walls lend themselves to a variety of facade treatments. The use of reveals (aesthetic joints), moldings, and colored concrete further adds to the design variations, Figure 28.34.

PANEL SHAPES AND SIZES

Another key design decision is the size, shape, and function of each panel. These include window wall panels, spandrel panels, and spandrel plus infill panels, Figure 28.35. The panels are generally one floor high, but those spanning two floors may be used.

PC wall panels are generally made as large as possible, limited only by the erection capacity of the crane, the transportation limitations, and the gravity load delivered by the panel to the structural frame. For structural reasons, the panels generally extend from column to column. Smaller panel sizes mean a larger number of panels, requiring a greater number of support connections, longer erection time, and, hence, a higher cost. If the scale of large panels is visually unacceptable, false joints can be incorporated in the panels, as shown in preceding images.

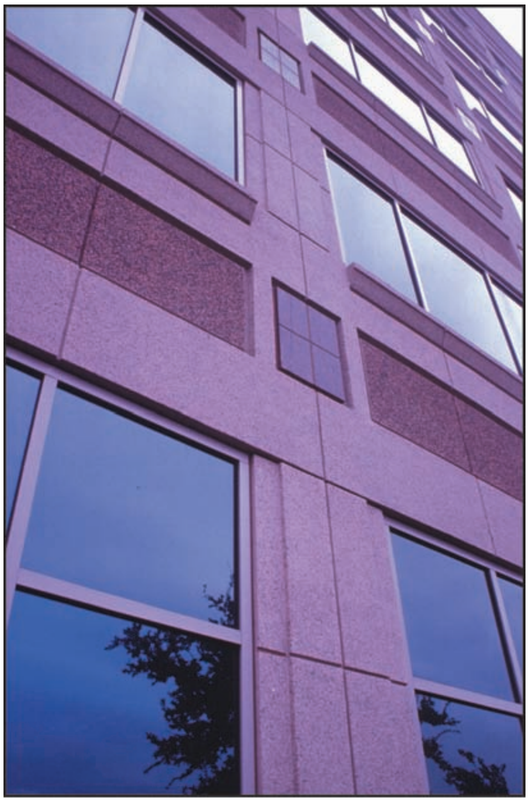


FIGURE 28.34(a) Lightly abrasive-blasted panels with a great deal of surface detailing.

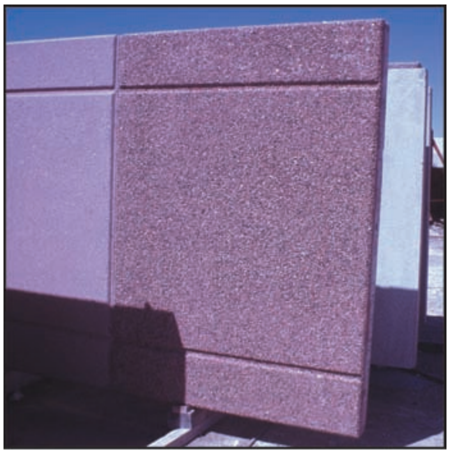


FIGURE 28.34(b) The part of this panel on the left side of the reveal is lightly abrasive-blasted, and the right side part is medium abrasive-blasted.

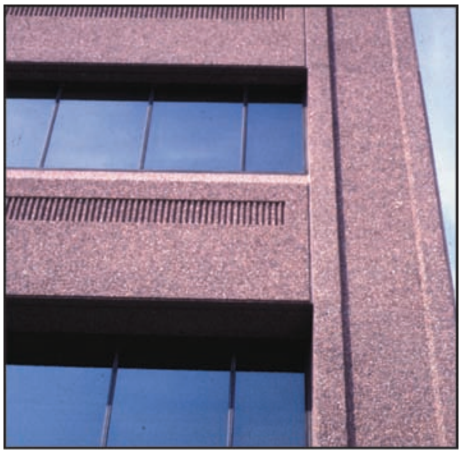


FIGURE 28.34(c) Panel with an exposed aggregate finish.

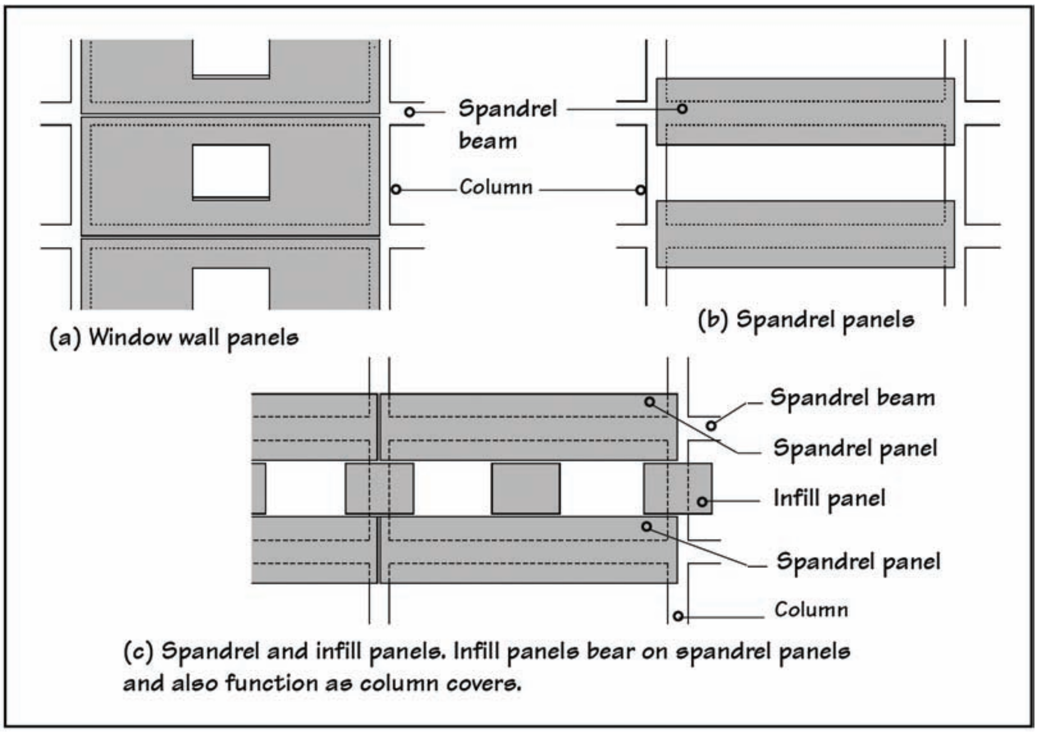

Spandrel beam
Column
(a) Window wall panels
(b) Spandrel panels
Spandrel beam
Spandrel panel
Infill panel
Spandrel panel
Column
(c) Spandrel and infill panels. Infill panels bear on spandrel panels and also function as column covers.

FIGURE 28.35 A few commonly used shapes of precast concrete curtain wall panels. Panels should preferably extend from column to column so that their dead load (which is delivered through two supports only) is transferred to the beam as close to the columns as possible (see Section 28.7).

CONCRETE STRENGTH

PC curtain wall panels are removed from the form as soon as possible to allow rapid turnover and reuse of the formwork. This implies that the 28-day concrete strength should be reasonably high so that when the panel is removed from the form, it can resist the stresses to which it may be subjected during the removal and handling processes.

The required concrete strength is also a function of the curtain wall's exposure, durability requirements, shape, and size of the panels. Flat panels may require higher strength (or greater thickness) compared to ribbed or profiled panels. Therefore, the strength of concrete must be established in consultation with the precast plant supplying the panels.

The most commonly used 28-day strength of concrete for PC curtain wall panels is 5,000 psi. This relatively high strength gives greater durability, greater resistance to rainwater penetration, and improved in-service performance. In other words, the panels are better able to resist stresses caused by the loads, building movement, and volume changes induced by thermal, creep, and shrinkage effects.

For aesthetic and economic reasons, a panel may use two mixes—a face (architectural) mix and a backup (structural) mix. In this case, the two mixes should have nearly equal expansion and contraction coefficients to prevent undue bowing and warping of the panel. In other words, the strength, slump, and water-cement ratios of the two mixes should be nearly the same.

Because panels are generally fabricated face down on flat formwork, the face mix is placed first, followed by the backup mix. The thickness of the face mix is a function of the aggregate size but should not be less than 1 in. The precaster's experience should be relied upon in determining the thicknesses and properties of the two mixes.

PANEL THICKNESS

The thickness of panels is generally governed by the handling (erection) stresses rather than the stresses caused by in-service loads. A concrete cover on both sides and the two-way reinforcement in a panel generally give a total of about 4 in. of thickness. Add to this the thickness that will be lost due to surface treatment, such as abrasive blasting and acid etching, and the total thickness of a PC wall panel cannot be less than 5 in.

However, because panel size is generally maximized, a panel thickness of less than 6 in. is rare. A thicker panel is not only stronger but is also more durable, is more resistant to water leakage, and has higher fire resistance. Greater thickness also provides greater heat-storage capacity (Chapter 5), making the panel less susceptible to heat-induced stresses.

MOCK-UP SAMPLE(S)

For PC curtain wall projects, the architect requires the precast plant to prepare and submit for approval a sample or samples of color, texture, and finish. The *mock-up* panels, when approved, are generally kept at the construction site and become the basis for judgment of all panels produced by the precast plant.

28.7 CONNECTING THE PC CURTAIN WALL TO A STRUCTURE

The connections of PC curtain wall panels to the building's structure are among the most critical items in a PC curtain wall project and are typically designed by the panel fabricator. Two types of connections are required in each panel:

- Gravity load connections
- Lateral load connections

There should be only two gravity load connections, also referred to as *bearing supports*, per panel located as close to the columns as possible. The lateral load connections, also referred to as *tiebacks*, may be as many as needed by structural considerations, generally two or more per panel, Figure 28.36.

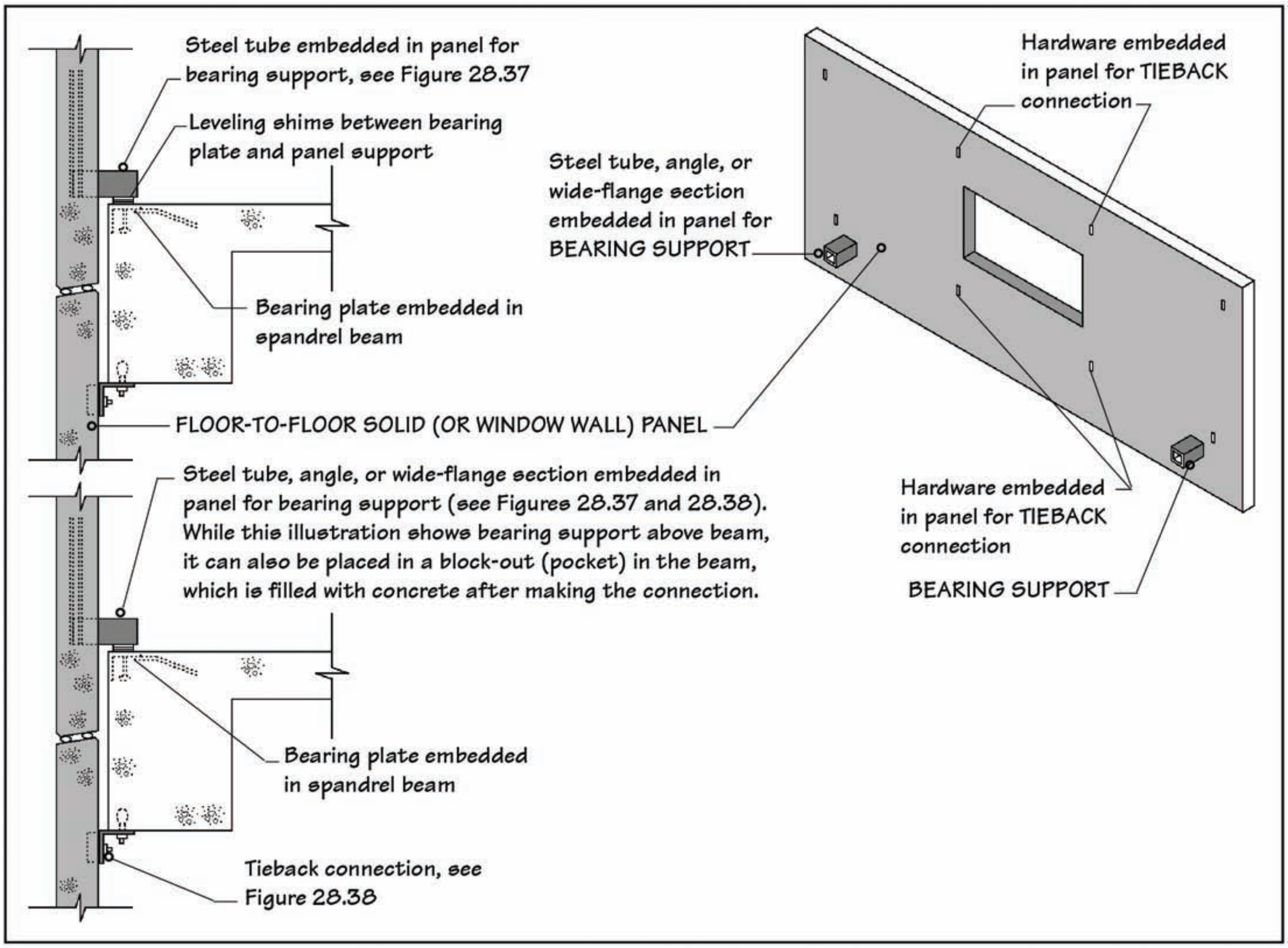

Steel tube embedded in panel for bearing support, see Figure 28.37
Leveling shims between bearing plate and panel support
Steel tube, angle, or wide-flange section embedded in panel for BEARING SUPPORT
Hardware embedded in panel for TIEBACK connection
Bearing plate embedded in spandrel beam
FLOOR-TO-FLOOR SOLID (OR WINDOW WALL) PANEL
Steel tube, angle, or wide-flange section embedded in panel for bearing support (see Figures 28.37 and 28.38). While this illustration shows bearing support above beam, it can also be placed in a block-out (pocket) in the beam, which is filled with concrete after making the connection.
Hardware embedded in panel for TIEBACK connection
BEARING SUPPORT
Bearing plate embedded in spandrel beam
Tieback connection, see Figure 28.38

FIGURE 28.36 Support connections for a typical floor-to-floor curtain wall panel.

BEARING SUPPORTS

A commonly used bearing support for floor-to-floor panels is provided by a section of steel tube, part of which is embedded in the panel and part of which projects out of the panel. The projecting part rests on the (steel angle) bearing plate embedded at the edge of the spandrel beam. Dimensional irregularities, both in the panel and in the structure, require the use of leveling shims (or bolts) under bearing supports during erection.

After the panels have been leveled, the bearing supports are welded to the bearing plate. The bearing support system is designed to allow the panel to move within its own plane so that the panel is not subjected to stresses induced by temperature, shrinkage, and creep effects.

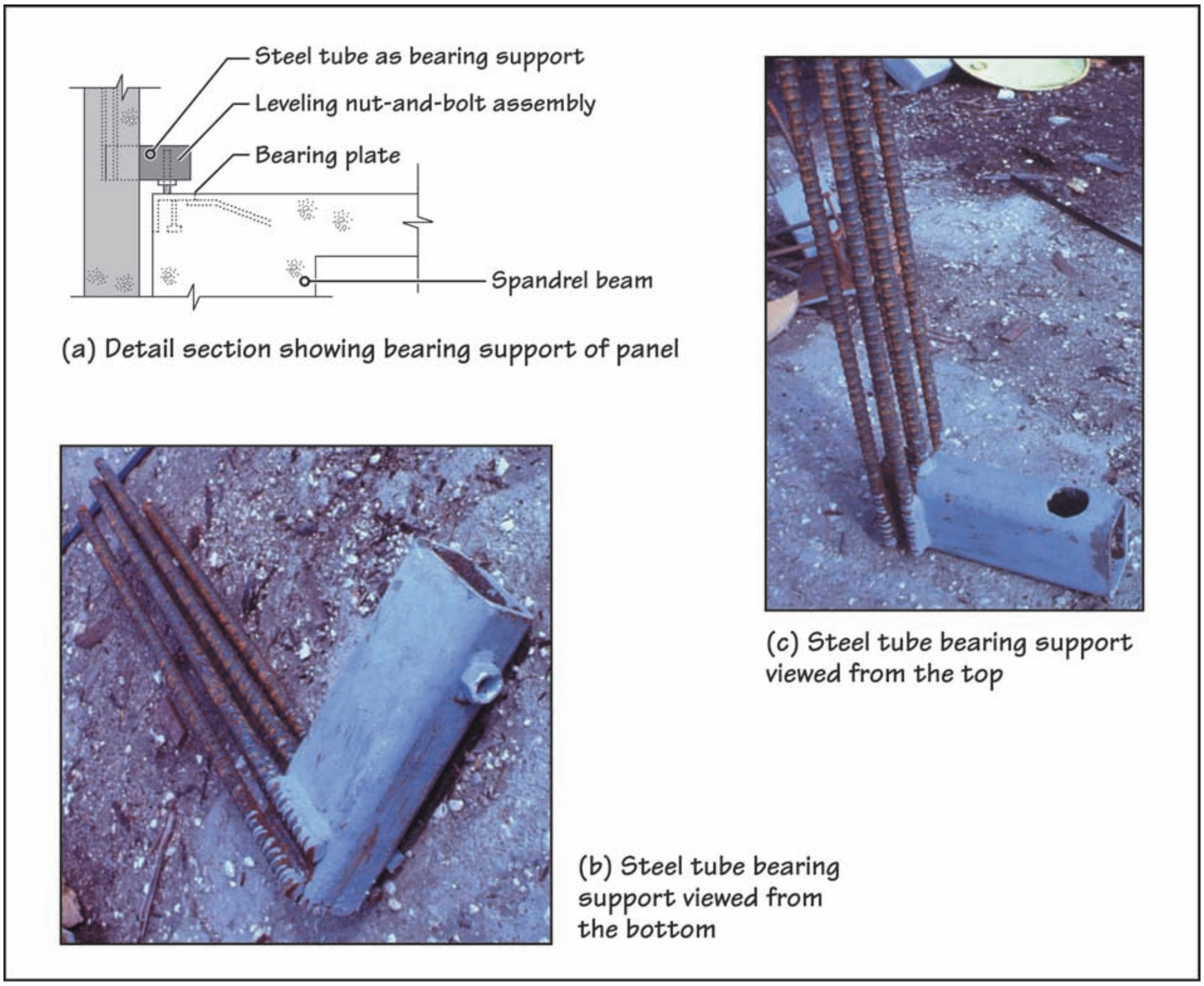
In place of leveling shims in a bearing support, a leveling bolt is often used, Figure 28.37. The choice between the shims and the bolt is generally left to the preference of the precast manufacturer and the erector. Alternatives to the use of steel tube for bearing supports are steel angles or a wide-flange (I-) section, Figure 28.38.

TIEBACKS

A lateral load connection (tieback) is designed to resist horizontal forces on the panel from wind and/or earthquake and due to the eccentricity of panel bearing. Therefore, it must be able to resist tension and compression perpendicular to the plane of the panel.

NOTE

The connection system of a PC curtain wall resembles that of a brick veneer connection system and is common to all types of curtain walls. The shelf angles in brick veneer provide the gravity load connection, and the anchors between the veneer and the backup wall provide the lateral load connection.


Steel tube as bearing support
Leveling nut-and-bolt assembly
Bearing plate
Spandrel beam

(a) Detail section showing bearing support of panel

(b) Steel tube bearing support viewed from the bottom

(c) Steel tube bearing support viewed from the top

FIGURE 28.37 Steel tube as bearing support and leveling nut and bolt.

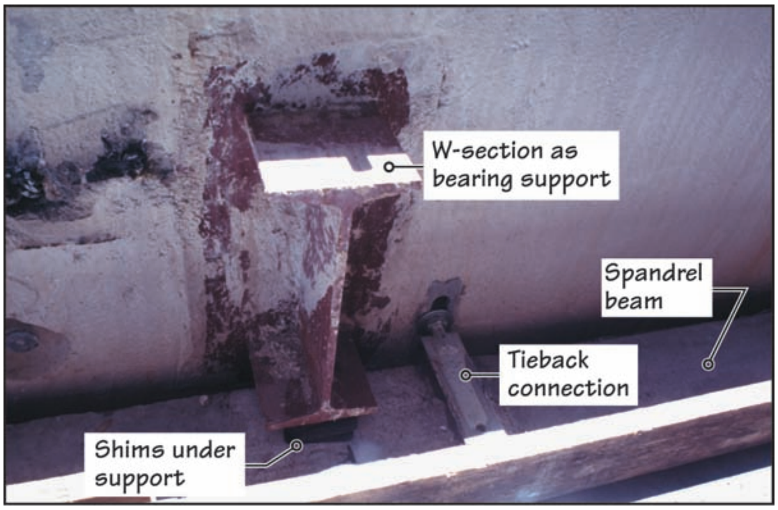

W-section as bearing support
Spandrel beam
Tieback connection
Shims under support

FIGURE 28.38 Wide-flange section used as bearing support in a PC panel.

A tieback is designed to allow movement within the plane of the panel. The connection must, however, permit adjustment in all three principal directions during erection. A typical tieback is shown in Figure 28.39; see also Figure 28.38.

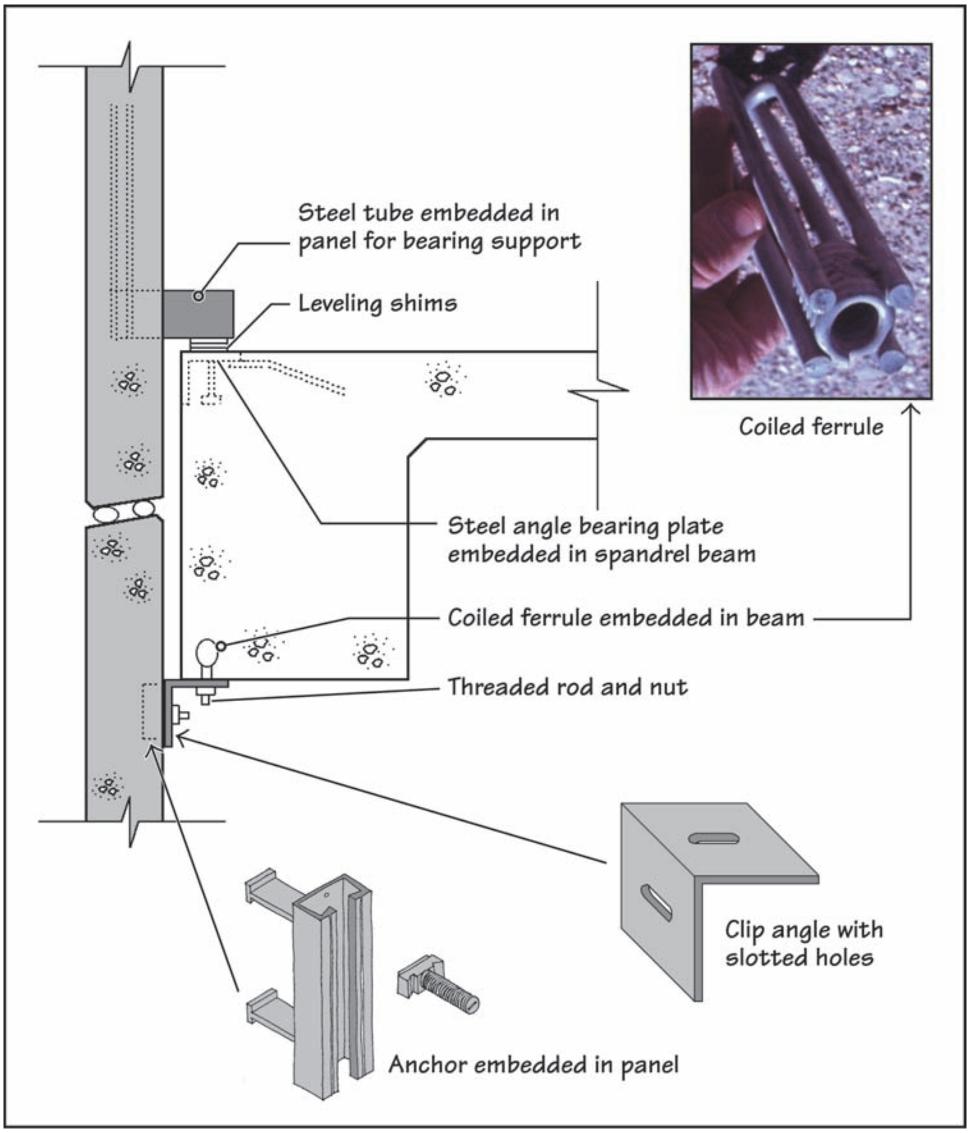

Steel tube embedded in panel for bearing support
Leveling shims
Coiled ferrule
Steel angle bearing plate embedded in spandrel beam
Coiled ferrule embedded in beam
Threaded rod and nut
Clip angle with slotted holes
Anchor embedded in panel

FIGURE 28.39 A typical tieback connection that allows three-way field adjustment during panel erection in addition to allowing in-service vertical deflection of the spandrel beam and thermal expansion/contraction of the panel.

SUPPORT SYSTEMS FOR SPANDREL PANELS AND INFILL PANELS

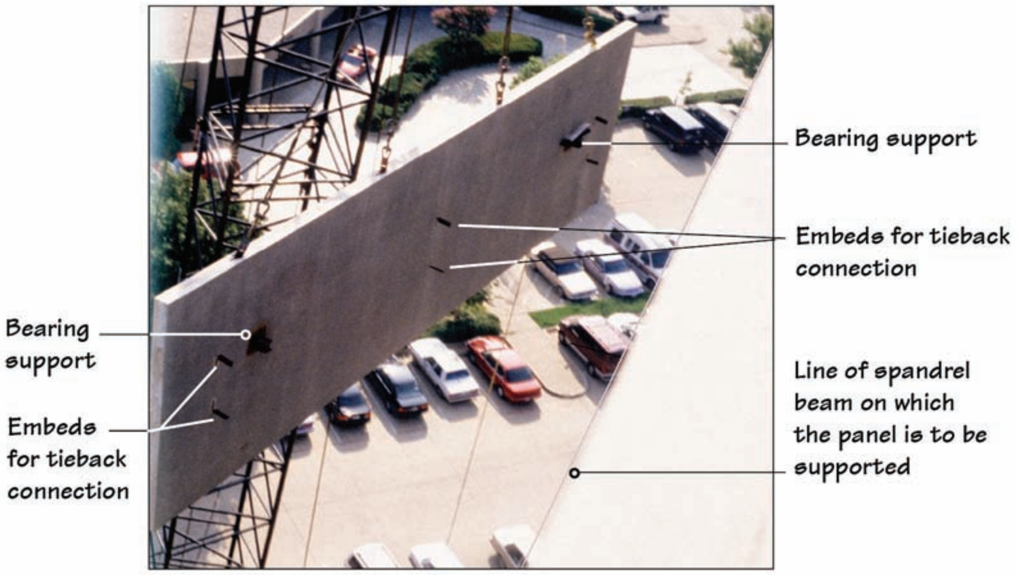
Support systems for a curtain wall consisting of spandrel and infill panels are shown in Figure 28.40; see also Figure 28.35(c).

PANELS AND STEEL–FRAME STRUCTURE

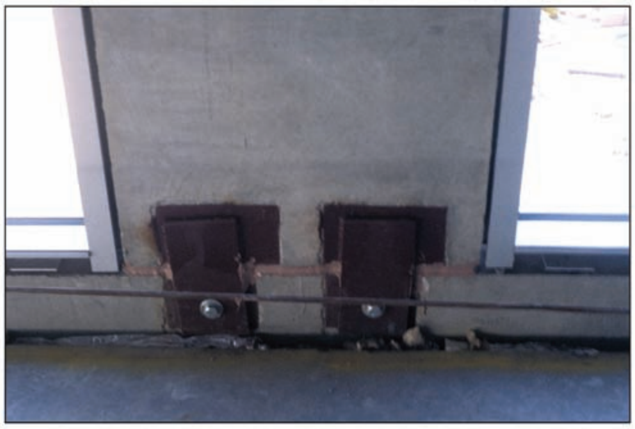
PC wall panels, which create eccentric loading on the spandrel beams, create torsion in the beams. Due to the lower torsional resistance of wide-flange steel beams, PC panels used with a steel-frame structure are generally designed to span from column to column and made to bear directly on them. Tiebacks, however, are connected to the spandrel beams.

CLEARANCE OF PANELS FROM THE STRUCTURAL FRAME

The Precast/Prestressed Concrete Institute (PCI) recommends a minimum horizontal clearance of 2 in. of precast panels from the building's structural frame.


Bearing support
Embeds for tieback connection
Line of spandrel beam on which the panel is to be supported
Bearing support
Embeds for tieback connection

(a) A PC spandrel panel being brought into its final position.



(b) Support connections for an infill panel bearing on a spandrel panel, see Figure 28.35.

FIGURE 28.40 Support connections for: **(a)** a spandrel panel and **(b)** an infill panel bearing on spandrel panel.

28.8 BRICK- AND STONE-FACED PC CURTAIN WALL

PC curtain wall panels may be faced with thin (clay) bricks at the time of casting the panels. Generally, $\frac{3}{4}$-in. to 1-in-thick bricks are used. They are available in various shapes, Figure 28.41. The bricks are placed in the desired pattern in the form, and the concrete is placed over them. To prevent the bricks from shifting during the placing operation, a rubber template is used, within which the bricks are placed, Figures 28.42 and 28.43. The template aligns the bricks and allows the concrete to simulate the mortar joints.

In well-designed and well-fabricated panels, it is generally difficult to distinguish between a site-constructed brick veneer wall and a brick-faced PC curtain wall. Brick-faced panels have the same advantages as other PC curtain wall panels—that is, no on-site construction and no scaffolding.

Thin bricks need to be far more dimensionally uniform than full-size bricks. With full-size bricks, dimensional nonuniformity is compensated for by varying the mortar thickness.

Because clay bricks expand by absorbing moisture from the atmosphere (moisture expansion), thin bricks should be allowed to season for a few weeks at the precaster's plant before being used. This reduces their inherent incompatibility with concrete, which shrinks on drying.

Although moisture expansion and drying shrinkage are the major causes of incompatibility between bricks and concrete, other differences between the two materials, such as the coefficient of thermal expansion and the modulus of elasticity, must also be considered. Because of these differences, a brick-faced concrete panel is subject to bowing due to differential expansion and contraction of the face and the backup.

Bowing can be reduced by increasing the stiffness of the panel. Using two layers of reinforcement is encouraged when the thickness of the panel permits. Additionally, some precasters use reverse curvature in the panels.

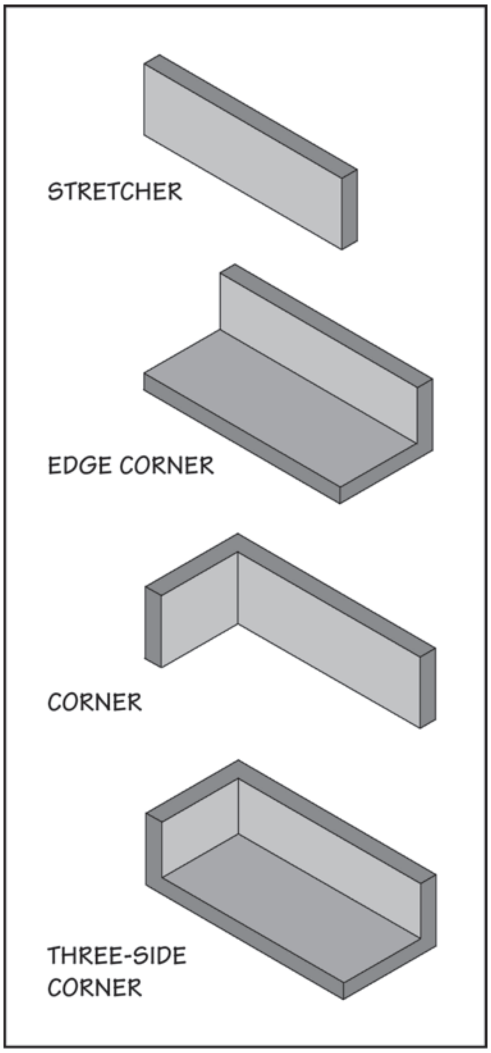


FIGURE 28.41 A few thin clay brick shapes.

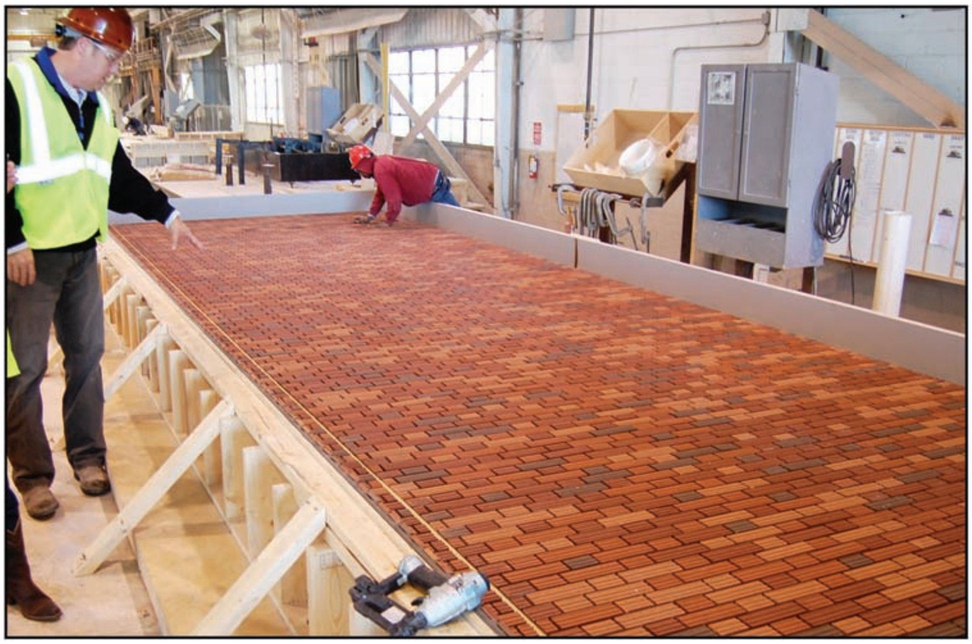


FIGURE 28.42 Preparation for casting a precast concrete curtain wall panel faced with thin bricks. Thin bricks are laid within the recessed spaces in a rubber template before the panel reinforcement and concrete are placed over the bricks.

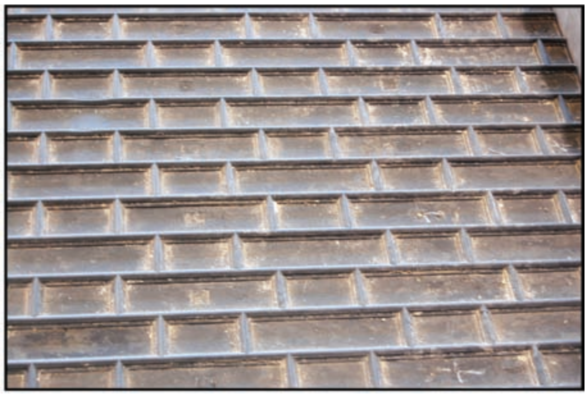


FIGURE 28.43 A typical reusable rubber template within which thin bricks are placed, shown in Figure 28.42.

The bond between concrete and bricks is obviously very important for a brick-faced concrete wall panel. The back surface of bricks used in brick-faced panels should contain grooves, ribs, or dovetail slots to develop an adequate bond. The bond between concrete and brick is measured by a shear strength test. The architect should obtain the test results from the brick manufacturer before specifying the bricks for use.

The bond between concrete and bricks is also a function of how absorptive the bricks are. Bricks with excessively high or excessively low water absorption give a poor bond. Bricks with high water absorption are subjected to freeze-thaw damage.

STONE VENEER–FACED PC PANELS

PC curtain wall panels can also be faced with (natural) stone veneer. The thickness of the veneer varies with the type of stone and the face dimensions of the veneer units. Granite and marble veneers are recommended to be at least $1\frac{1}{4}$ in. (3 cm) thick. Limestone veneer should be at least 2 in. (5 cm) thick.

The face dimensions of individual veneer units are generally limited to 25 ft^2 for granite and 15 ft^2 for marble or limestone. Thus, a typical PC curtain wall panel has several veneer units anchored to it.

The veneer is anchored to the concrete panel using stainless steel flexible dowels, whose diameter varies from $\frac{3}{16}$ in. to $\frac{5}{8}$ in. Two dowel shapes are commonly used—a U-shaped (hairpin) dowel and a pair of cross-stitch dowels, Figure 28.44. The dowels are inserted in holes drilled in the veneer. The dowel holes, which are $\frac{1}{16}$ in. to $\frac{1}{8}$ in. larger in diameter than the diameter of the dowels, are filled with epoxy or an elastic, fast-curing silicone sealant. Unfilled holes allow water to seep in, leading to staining of the veneer and freeze-thaw damage.

Because the dowels are thin and flexible, they allow relative movement between the veneer and the backup. To further improve their flexibility, rubber washers are used with the dowels at the interface of the veneer and the backup.

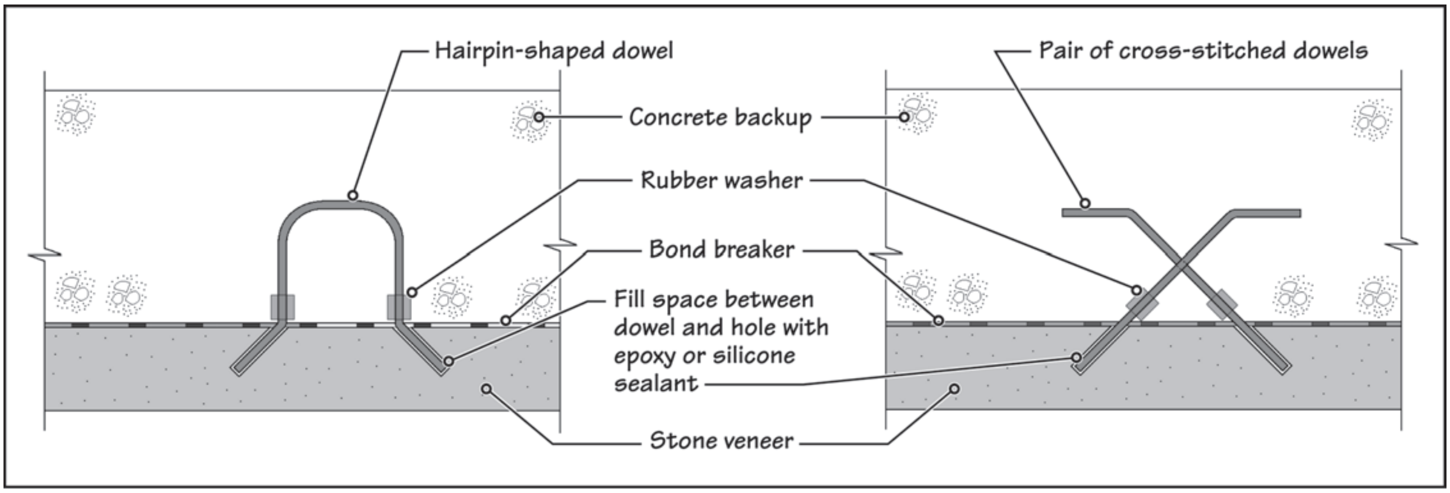

Hairpin-shaped dowel
Pair of cross-stitched dowels
Concrete backup
Rubber washer
Bond breaker
Fill space between dowel and hole with epoxy or silicone sealant
Stone veneer

FIGURE 28.44 Two commonly used dowel anchors.

The depth of anchor in the veneer is nearly half the veneer thickness. The anchorage into concrete varies, depending on the type of stone and the loads imposed on the panel.

There should be no bond between stone veneer and the backup concrete to prevent bowing of the panel and cracking and staining of the veneer. To prevent the bond, a bond breaker is used between the veneer and the backup. The bond breaker is either a 6-mil to 10-mil-thick polyethylene sheet or a $\frac{1}{8}$ in. to $\frac{1}{4}$-in.-thick compressible, closed-cell polyethylene foam board. Foam board is preferred because it gives better movement capability with an uneven stone surface.

A PC curtain wall panel may be fully veneered with stone or the veneer may be used only as an accent or feature strip on part of the panel.

OTHER FORM LINERS

Because concrete is a moldable material, several geometric and textured patterns can be embossed on panel surface using form liners. An architect can select from a variety of standard form liners or have them specially manufactured for a large project (see Section 22.4).

28.9 DETAILING A PC CURTAIN WALL

A typical PC curtain wall is backed by an infill steel stud wall. The stud wall provides the interior finish and includes the insulation, as well as electrical and other utility lines. Because the backup wall is not subjected to wind loads, it needs to be designed only for incidental lateral loads from the building's interior (minimum 5 psf). Therefore, a fairly lightweight backup wall is adequate. This contrasts with a backup stud wall in a brick veneer wall, which must be designed to resist wind loads and be sufficiently stiff to have a relatively small deflection.

Figure 28.45 shows a representative detail of a PC curtain wall with a steel stud backup wall. The space between the panels and the backup wall may be filled with rigid insulation, if needed.

WATER INTRUSION CONTROL AND JOINTS BETWEEN PANELS

Concrete walls are sufficiently water resistant. Therefore, PC curtain walls do not require the same level of water intrusion control as brick veneer walls. However, the joints between panels must be treated with a backer rod and sealant.

A minimum joint width of 1 in. between panels is generally recommended. Although a single-stage joint is commonly used, the preferred method is to use a two-stage joint system, consisting of a pair of backer rod and sealant bead combinations. One backer rod and sealant bead combination is placed toward the outer surface of the joint and the other is placed toward the inner surface, Figure 28.46.

The outer seal provides a weather barrier and contains weep holes. The inner seal is continuous, without any openings, and is meant to provide an air barrier. The air barrier must extend continuously over a panel and across the joint between panels. The provision of the air barrier and the openings in the exterior seal make the two-stage joint system function as a rain screen (see Chapter 27).

Both inner and outer seals should be applied from the outside to avoid discontinuities at the spandrel beams and floor slabs. This requires a deep-stem roller to push the backer rod deep into the joint and a long-nozzle sealant gun.

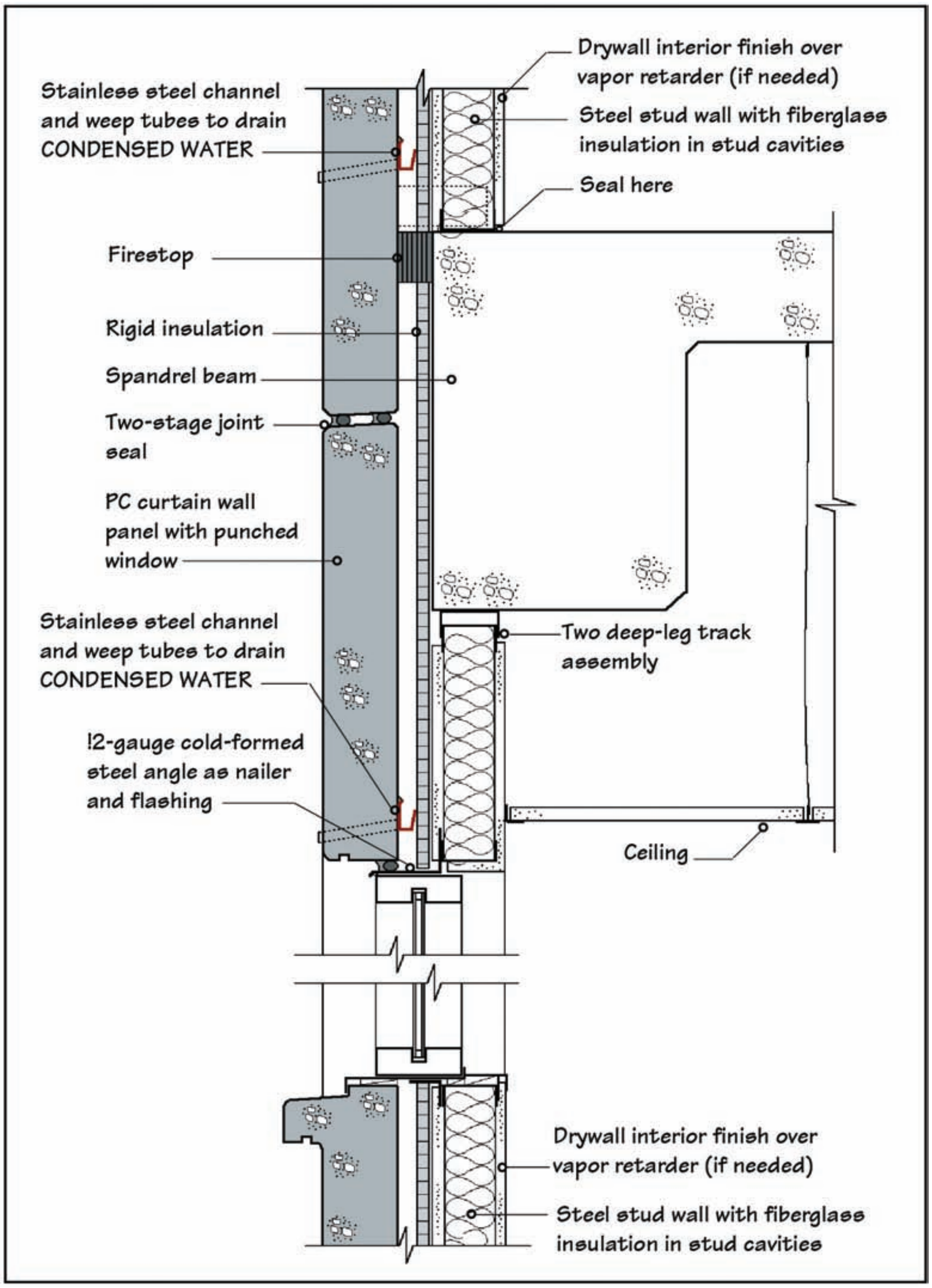

Stainless steel channel and weep tubes to drain CONDENSED WATER
Drywall interior finish over vapor retarder (if needed)
Steel stud wall with fiberglass insulation in stud cavities
Seal here
Firestop
Rigid insulation
Spandrel beam
Two-stage joint seal
PC curtain wall panel with punched window
Stainless steel channel and weep tubes to drain CONDENSED WATER
Two deep-leg track assembly
!2-gauge cold-formed steel angle as nailer and flashing
Ceiling
Drywall interior finish over vapor retarder (if needed)
Steel stud wall with fiberglass insulation in stud cavities

FIGURE 28.45 A typical PC curtain wall (schematic) detail.

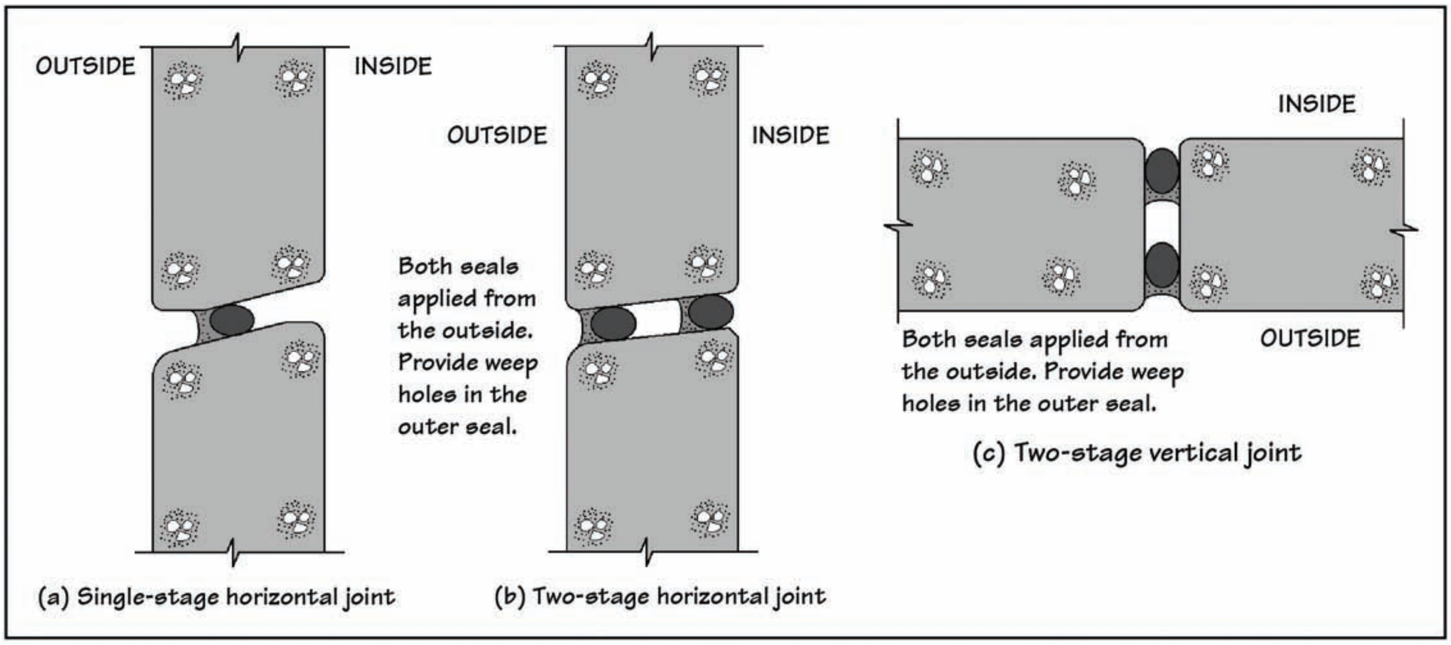

OUTSIDE
INSIDE
OUTSIDE
INSIDE
Both seals applied from the outside. Provide weep holes in the outer seal.
INSIDE
OUTSIDE
Both seals applied from the outside. Provide weep holes in the outer seal.
(c) Two-stage vertical joint
(a) Single-stage horizontal joint
(b) Two-stage horizontal joint

FIGURE 28.46 Treatment of joints between PC curtain wall panels.

In addition to sealed joints, PC curtain walls should be provided with stainless steel channels and weep tubes to collect and drain any condensed water that may collect on the back face of the panels (see Figure 28.45).

INSULATED, SANDWICHED PANELS

PC curtain wall panels with rigid plastic foam insulation sandwiched between two layers of concrete may be used to provide unbroken continuous insulation. A sandwich panel consists of an outer layer of concrete and an inner layer of concrete, in which both layers are connected together with ties through an intermediate layer of rigid plastic foam insulation.

The outer layer is a nonstructural layer, whereas the inner layer is designed to carry the entire load and transfer it to the structural frame. The panel is fabricated by first casting the concrete for the nonstructural layer. This is followed by embedding the ties and placing the insulation boards over the ties. The insulation is provided with pre-drilled holes at required locations based on the structural requirements. The tie profile is such that the lower part of each tie gets embedded into the face concrete layer below the insulation. The upper part of the tie projects above the insulation by a predetermined height, which gets embedded into the structural layer of concrete cast above the insulation. Figures 28.47 through 28.50 illustrate the construction of an insulated, sandwich panel.

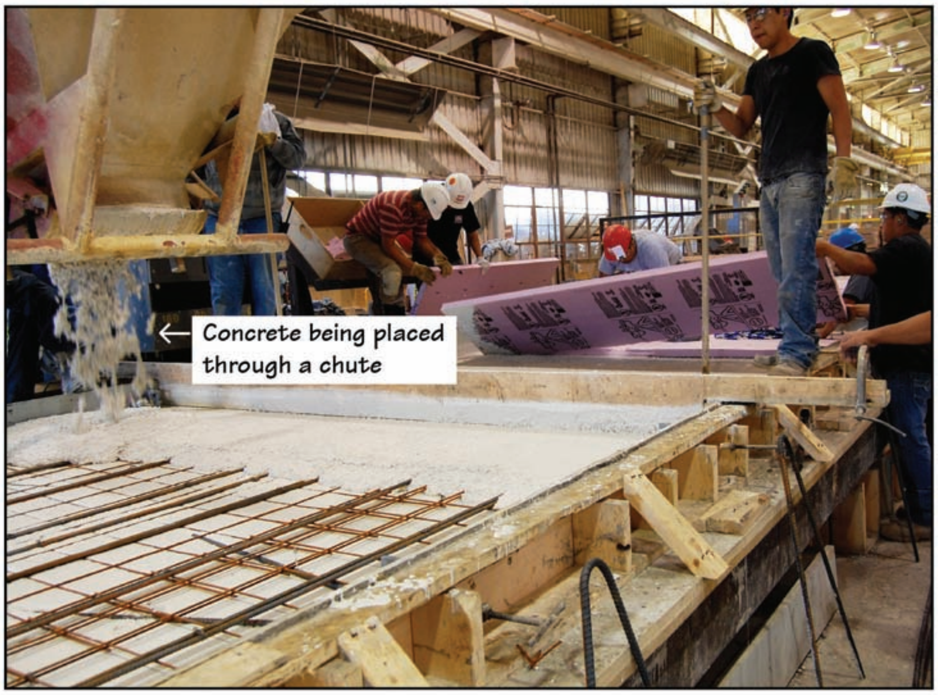


FIGURE 28.47 Placement of face (nonstructural) concrete in an insulated sandwich panel. Notice that the face concrete is made with white Portland cement and has its own reinforcement.

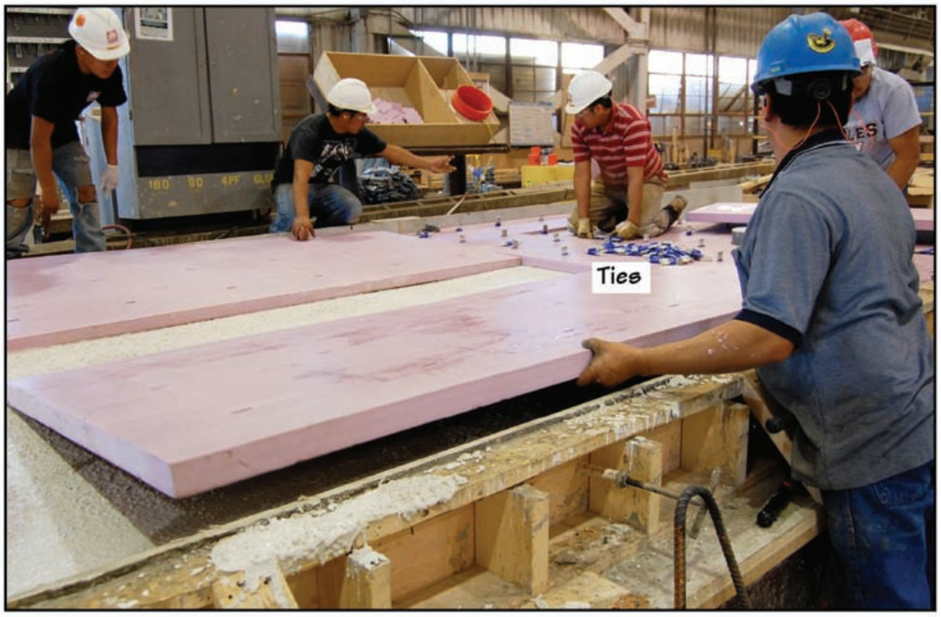


FIGURE 28.48 As soon as the face concrete has been placed and struck to a level surface, rigid board insulation is placed over it. Subsequently, high-strength plastic ties are inserted in predrilled holes in the insulation. A part of the tie is embedded in face concrete, a part lies within the insulation and its projecting part gets embedded in backup (structural) concrete to follow.

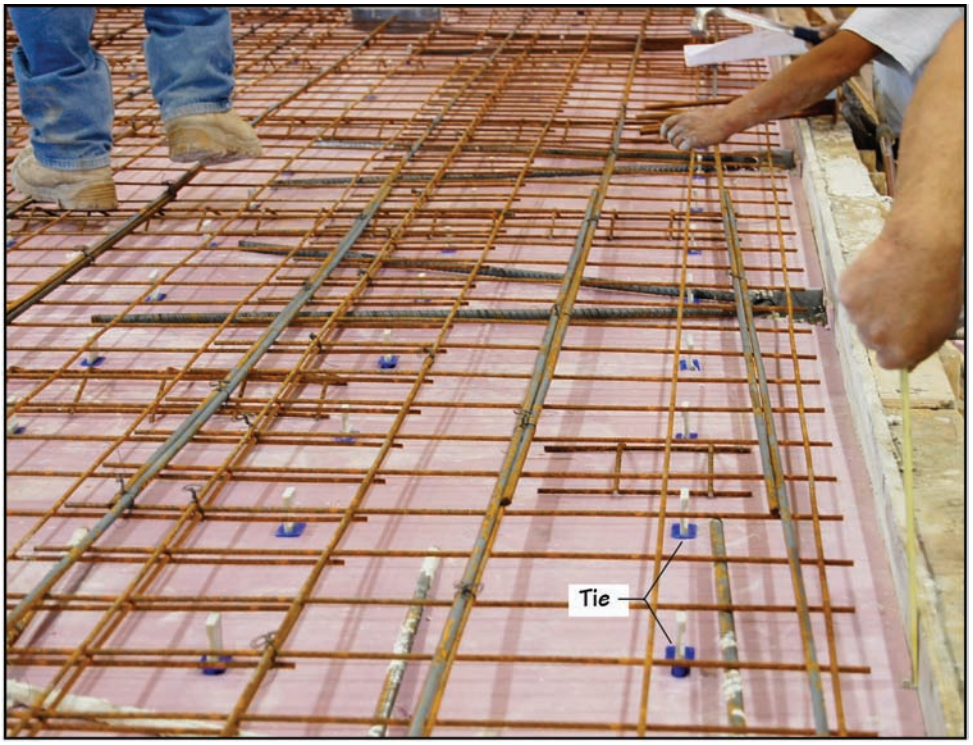


FIGURE 28.49 After the insulation and ties are in place, reinforcement for the structural (backup) concrete layer is placed. Notice the ties projecting above the insulation.

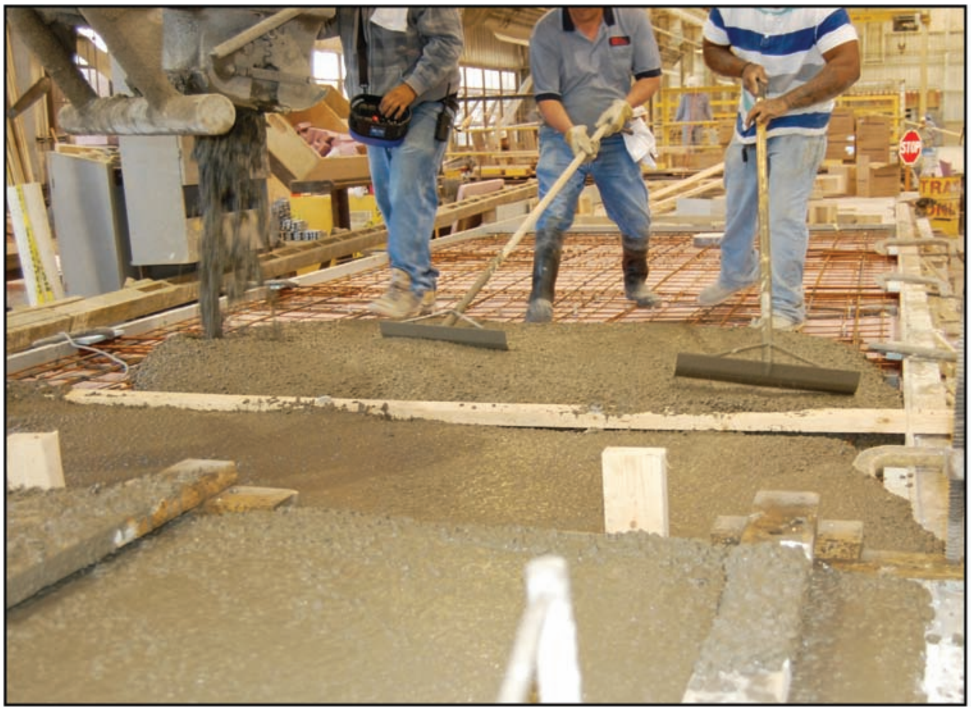


FIGURE 28.50 The final step in the fabrication of an insulated sandwich precast concrete curtain wall panel consists of placing the concrete for the structural layer. Notice that the concrete in this layer is made with normal (gray) Portland cement.

PRACTICE **QUIZ**

Each question has only one correct answer. Select the choice that best answers the question.

22. The strength of concrete used in precast concrete curtain walls is generally
- **a.** greater than or equal to 3,000 psi.
- **b.** greater than or equal to 4,000 psi.
- **c.** greater than or equal to 5,000 psi.
- **d.** none of the above.

23. Precast concrete curtain wall panels are generally
- **a.** cast on the construction site.
- **b.** fabricated by a ready-mix concrete plant and transported to the construction site.
- **c.** (a) or (b).
- **d.** none of the above.

24. The number of bearing supports in a precast concrete curtain wall panel must be
- **a.** one.
- **b.** two.
- **c.** three.
- **d.** four.
- **e.** between three and six.

25. The structural design of precast concrete curtain wall panels is generally the responsibility of the
- **a.** structural engineer, who designs the structural frame of the building in which the panels are to be used.
- **b.** structural engineer retained by the panel fabricator.
- **c.** structural engineer retained by the general contractor of the building.
- **d.** structural engineer specially retained by the owner.
- **e.** none of the above.

(*Continued*)

26. During the erection of precast concrete curtain wall panels, the panels are leveled. The leveling of the panels is provided in the
a. panels' bearing supports.
b. panels' tieback connections.
c. (a) or (b).
d. (a) and (b).

27. The bricks used in brick-faced concrete curtain wall panels are generally
a. of the same thickness as those used in brick veneer construction.
b. thicker than those used in brick veneer construction.
c. thinner than those used in brick veneer construction.
d. any one of the above, depending on the building.

28. A bond break such as a polyethylene sheet membrane is generally used between the concrete and bricks in a brick-faced precast concrete curtain wall panel.
a. True **b.** False

29. The connection between the natural stone facing and the backup concrete in a stone-faced precast concrete curtain wall panel is obtained by
a. the roughness of the stone surface that is in contact with the concrete.
b. nonmoving steel dowels.
c. flexible steel dowels.
d. any one of the above.

28.10 GLASS FIBER–REINFORCED CONCRETE (GFRC) CURTAIN WALL

As the name implies, glass fiber–reinforced concrete (GFRC) is a type of concrete whose ingredients are Portland cement, sand, glass fibers, and water. Glass fibers provide tensile strength to concrete. Unlike a precast concrete panel, which is reinforced with steel bars, a GFRC panel does not require steel reinforcing.

The fibers are 1 in. to 2 in. long, and are thoroughly mixed and randomly dispersed in the mix. The random and uniform distribution of fibers not only provides tensile strength, but also gives toughness and impact resistance to a GFRC panel. Because normal glass fibers are adversely affected by wet Portland cement (due to the presence of alkalies in Portland cement), the fibers used in a GFRC mix are alkali-resistant (AR) glass fibers.

GFRC SKIN AND COLD-FORMED STEEL FRAME

A GFRC curtain wall panel consists of three main components:

- GFRC skin
- Cold-formed steel backup frame
- Anchors that connect the skin to the steel backup frame

Of these three components, only the skin is made of GFRC, which is generally $\frac{1}{2}$ in. to $\frac{3}{4}$ in. thick. The skin is anchored to a frame consisting of cold-formed (galvanized) steel members, Figure 28.51. In this combination, the GFRC skin transfers the loads to the frame, which, in turn, transfers the loads to the building's structure. The size and spacing of backup frame members depend on the overall size of the panel and the loads to which it is subjected.

FLEX ANCHORS

The skin is hung 2 in. (or more) away from the face of the frame using bar anchors. The gap between the skin and the frame is essential because it allows differential movement between the skin and the frame, particularly during the period when the fresh concrete in the skin shrinks as water evaporates.

The anchors are generally $\frac{3}{8}$-in.-diameter steel bars bent into an L shape. To provide corrosion resistance, cadmium-plated steel is generally used for the anchors. One end of the anchor is welded to the frame, and the other end is embedded in the skin. The skin is thickened around the anchor embedment. The thickened portion of the skin is referred to as a *bonding pad*, Figure 28.52.

The purpose of the anchors is to transfer both gravity and lateral loads from the skin to the frame. In doing so, the anchors must be fairly rigid in the plane perpendicular to the panel; that is, they should be able to transfer the loads without any deformation in the anchors.

However, the skin will experience in-plane dimensional changes due to moisture and temperature effects. The anchor must, therefore, have sufficient flexibility to allow these changes to occur without excessively stressing the skin. One way of achieving this goal is to flare the anchor away from the frame and weld it to the frame member at the far end, Figure 28.53. The term *flex anchor* underscores the importance of anchor flexibility.

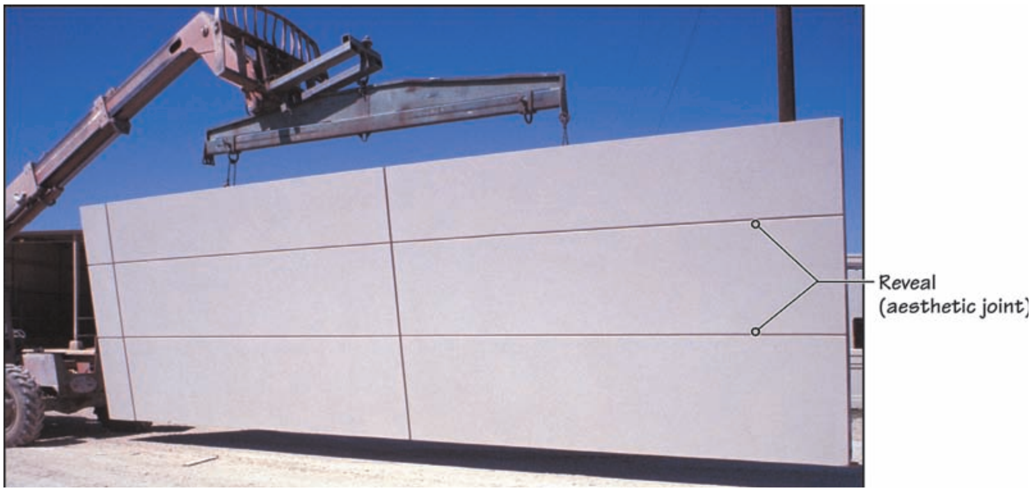

Reveal
(aesthetic joint)

FIGURE 28.51(a) The front face of a large GFRC panel after light abrasive blasting. It is being lifted for storage in the fabricator's shed.

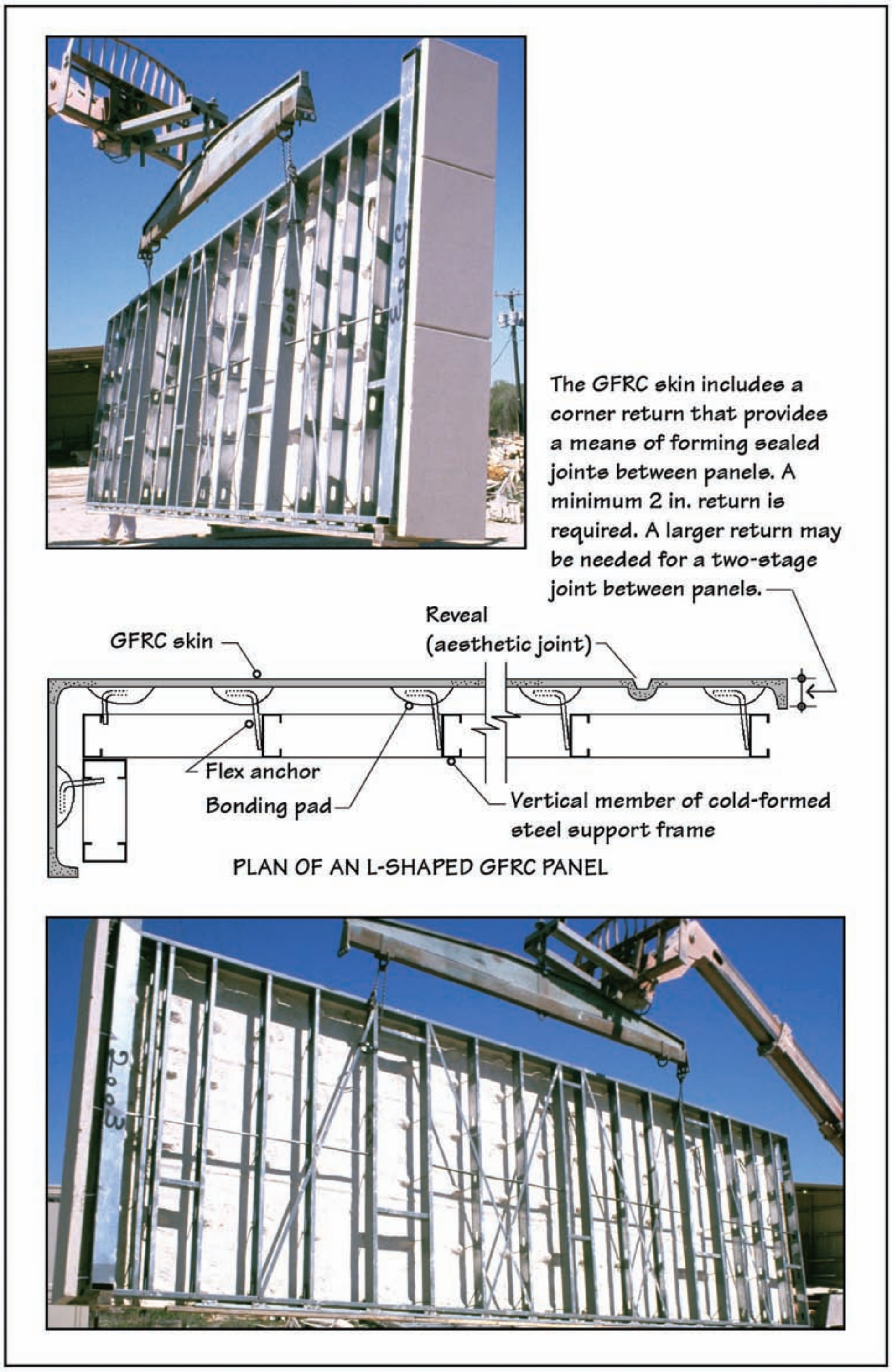

The GFRC skin includes a corner return that provides a means of forming sealed joints between panels. A minimum 2 in. return is required. A larger return may be needed for a two-stage joint between panels.
Reveal
(aesthetic joint)
GFRC skin
Flex anchor
Bonding pad
Vertical member of cold-formed steel support frame
PLAN OF AN L-SHAPED GFRC PANEL

FIGURE 28.51(b) The side and back faces of an L-shaped GFRC panel showing the supporting cold-formed steel frame.

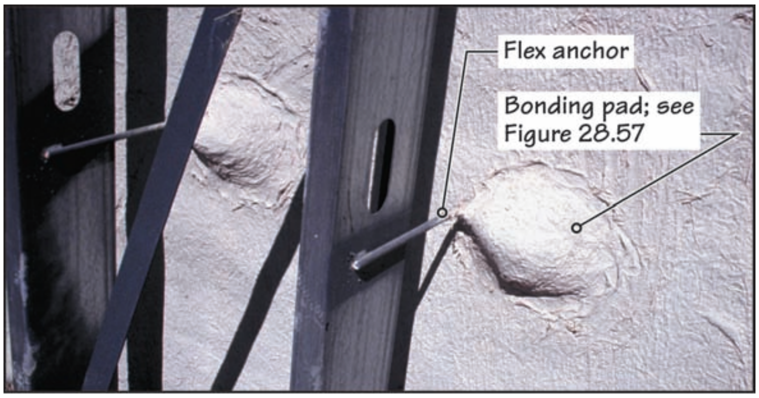


FIGURE 28.52 Bonding pads and flex anchors.

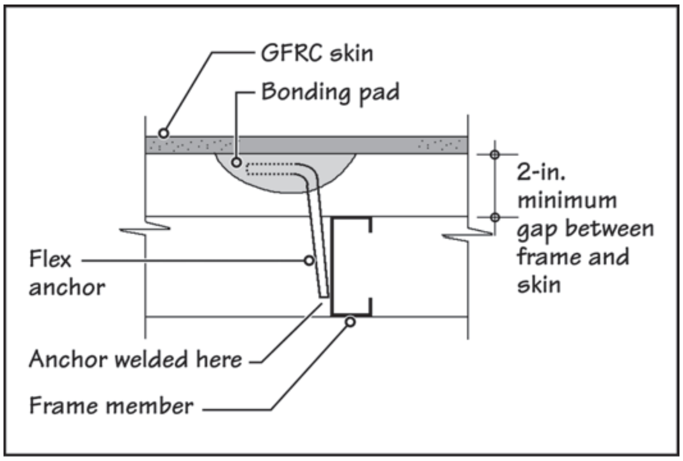


FIGURE 28.53 Flex anchor detail highlighting the flexibility of a flex anchor.

PANEL SHAPES

Like the precast concrete curtain wall panels, GFRC curtain wall panels can be formed into different shapes, depending on the building's facade. The most commonly used panels are floor-to-floor panels (Figure 28.51), window wall panels, and spandrel panels, similar to PC curtain wall panels. A spandrel panel is essentially a solid panel of smaller height than a floor-to-floor panel. Because the panels can be configured in several ways for a given facade, the architect must work with the GFRC fabricator before finalizing the panel shapes.

28.11 FABRICATION OF GFRC PANELS

Figures 28.54 to 28.57 show the six-step process of fabricating a GFRC panel.

- *Preparing the Mold*: The mold must be fabricated to the required shape, Figure 28.54(a). The mold generally consists of plywood, but other materials, such as steel or plastics, may be used. A form-release compound is applied to the mold before applying the GFRC mix to facilitate the panel's removal from the mold.
- *Applying the Mist Coat*: Before GFRC mix is sprayed on the panel, a thin cement-sand slurry coat, referred to as a *mist coat*, is sprayed on the mold, Figure 28.54(b). Because the mist coat does not contain any glass fibers, it gives a smooth, even surface to the panel. The thickness of the mist coat is a function of the finish the panel face is to receive. If the panel face is to be lightly abrasive-blasted, a $\frac{1}{8}$-in.-thick mist coat is adequate.
- *Applying the GFRC Mix*: Soon after the mist coat is applied, the GFRC mix is sprayed on the mold, Figure 28.55(a). The GFRC mix consists of (white) Portland cement and sand slurry mixed with about 5% (by weight) of glass fibers. Because air may be trapped in the mix during spraying, the mix is consolidated after completion of the spray application by rolling, tamping, or troweling, Figure 28.55(b).
- *Frame Placement*: After the GFRC spray is completed, a cold-formed steel support frame is placed against the skin, leaving the required distance between the skin and the frame, Figure 28.56.
- *Bonding Pads*: Finally, bonding pads are formed at each anchor using the same mix as that used for the skin, Figure 28.57.
- *Removing the Panel From the Mold and Curing*: The panel (skin and frame) is generally removed from the mold 24 h after casting and subsequently cured for a number of days. Because the panel has not yet gained sufficient strength, special care is needed during its removal.

SURFACE FINISHES ON GFRC PANELS

The standard finish on a GFRC panel is a light abrasive-blasted finish to remove the smoothness of the surface obtained from the mist coat. However, a GFRC panel can also be given an exposed aggregate finish, which results in a surface similar to that of a precast concrete panel.

To obtain an exposed aggregate finish, the mist coat is replaced by a concrete layer, referred to as a *face mix*. The thickness of the face mix is about $\frac{3}{8}$ in., and the aggregate used in the face mix is between $\frac{3}{16}$ in. and $\frac{1}{4}$ in. The exposure of aggregate is obtained by abrasive blasting or acid etching.

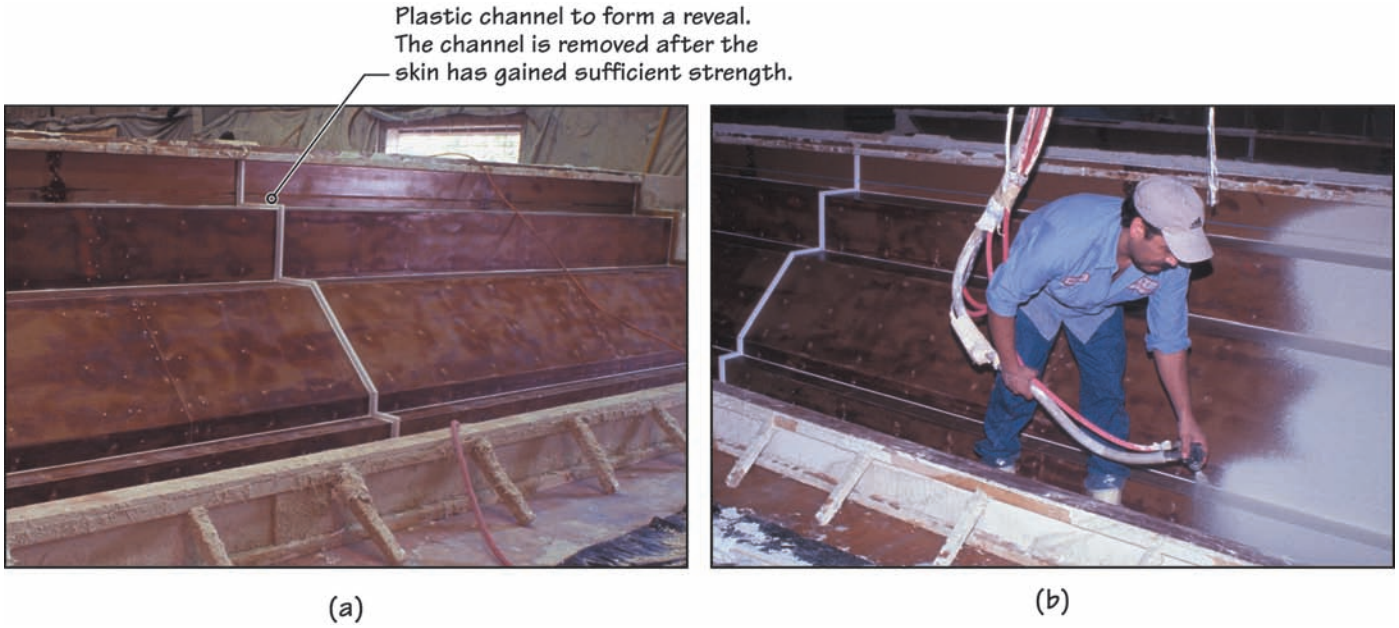

Plastic channel to form a reveal. The channel is removed after the skin has gained sufficient strength.
(a)
(b)

FIGURE 28.54 **(a)** The mold of a roof cornice GFRC panel. **(b)** Application of a mist coat on the mold.

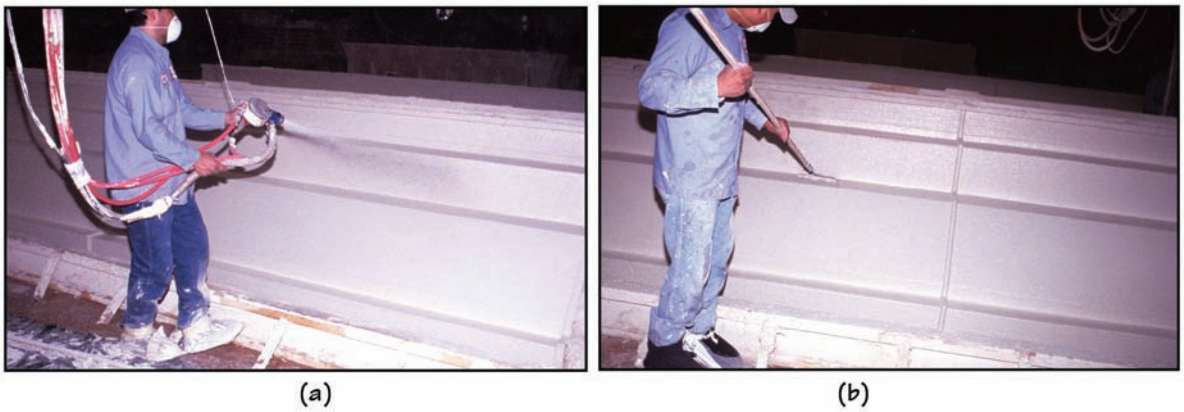


FIGURE 28.55 **(a)** Spraying of a GFRC mix over the mist coat. **(b)** Consolidating the GFRC mix using a roller around the bends, edges, and corners.

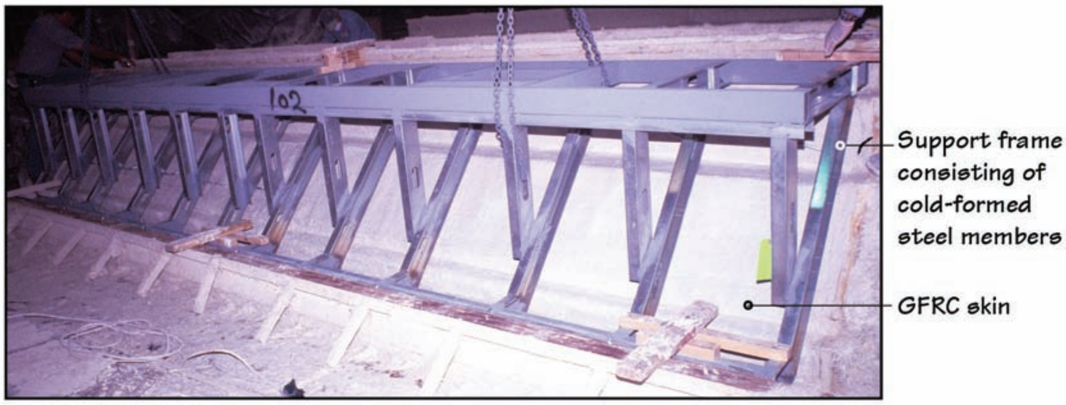

Support frame consisting of cold-formed steel members
GFRC skin

FIGURE 28.56 After spraying and consolidating the mix for the GFRC skin on the mold, a cold-formed steel supporting frame is placed against the mold and bonding pads are formed.

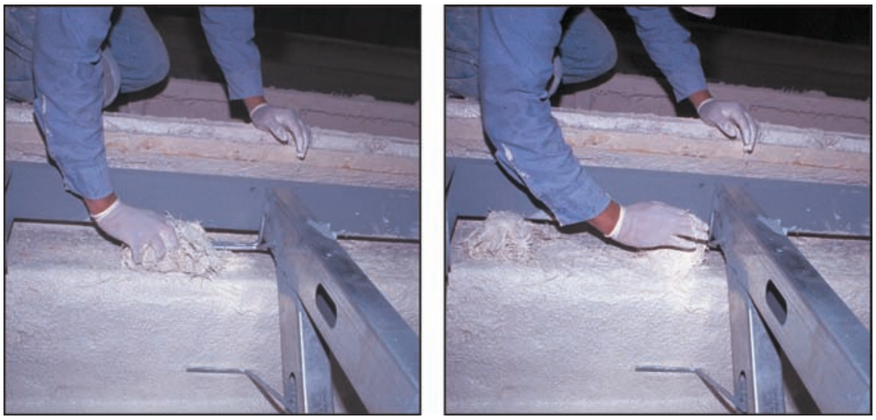
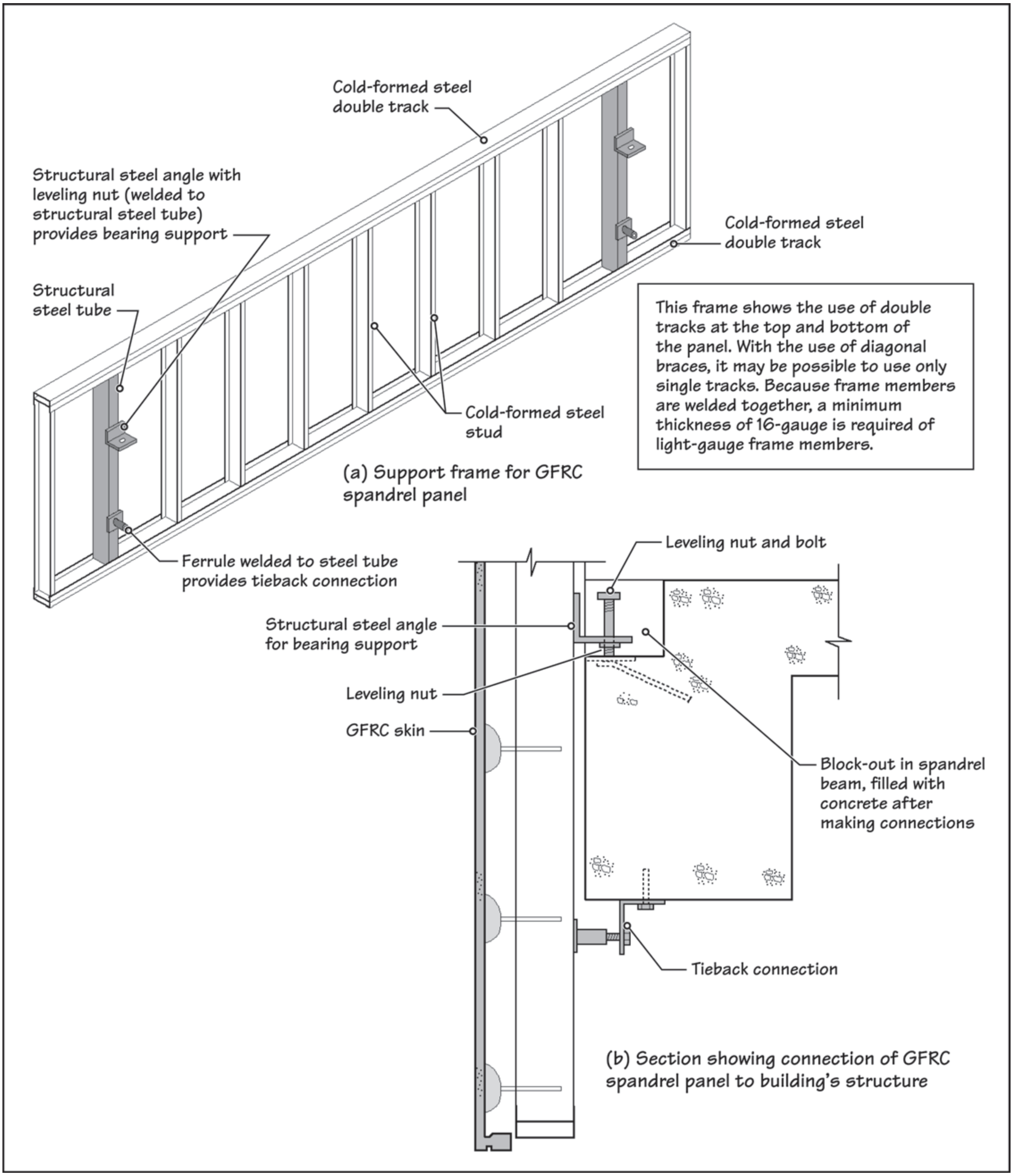


FIGURE 28.57 Making a bonding pad (also see Figures 28.52 and 28.53).

28.12 DETAILING A GFRC CURTAIN WALL

A GFRC panel is connected to the building's structure in a system similar to that of a precast concrete panel. In other words, a GFRC panel requires two bearing connections and two or more tieback connections. However, because GFRC panels are much lighter than the precast concrete panels, their connection hardware is lighter.

As with precast concrete curtain walls, the structural design of panels and their support connections is generally the responsibility of the panel fabricator. Figures 28.58 and 28.59 show two alternative schematics for the connection of a GFRC spandrel panel to the building's structure.


Cold-formed steel double track
Structural steel angle with leveling nut (welded to structural steel tube) provides bearing support
Cold-formed steel double track
Structural steel tube
Cold-formed steel stud
Ferrule welded to steel tube provides tieback connection
Leveling nut and bolt
Structural steel angle for bearing support
Leveling nut
GFRC skin
Block-out in spandrel beam, filled with concrete after making connections
Tieback connection

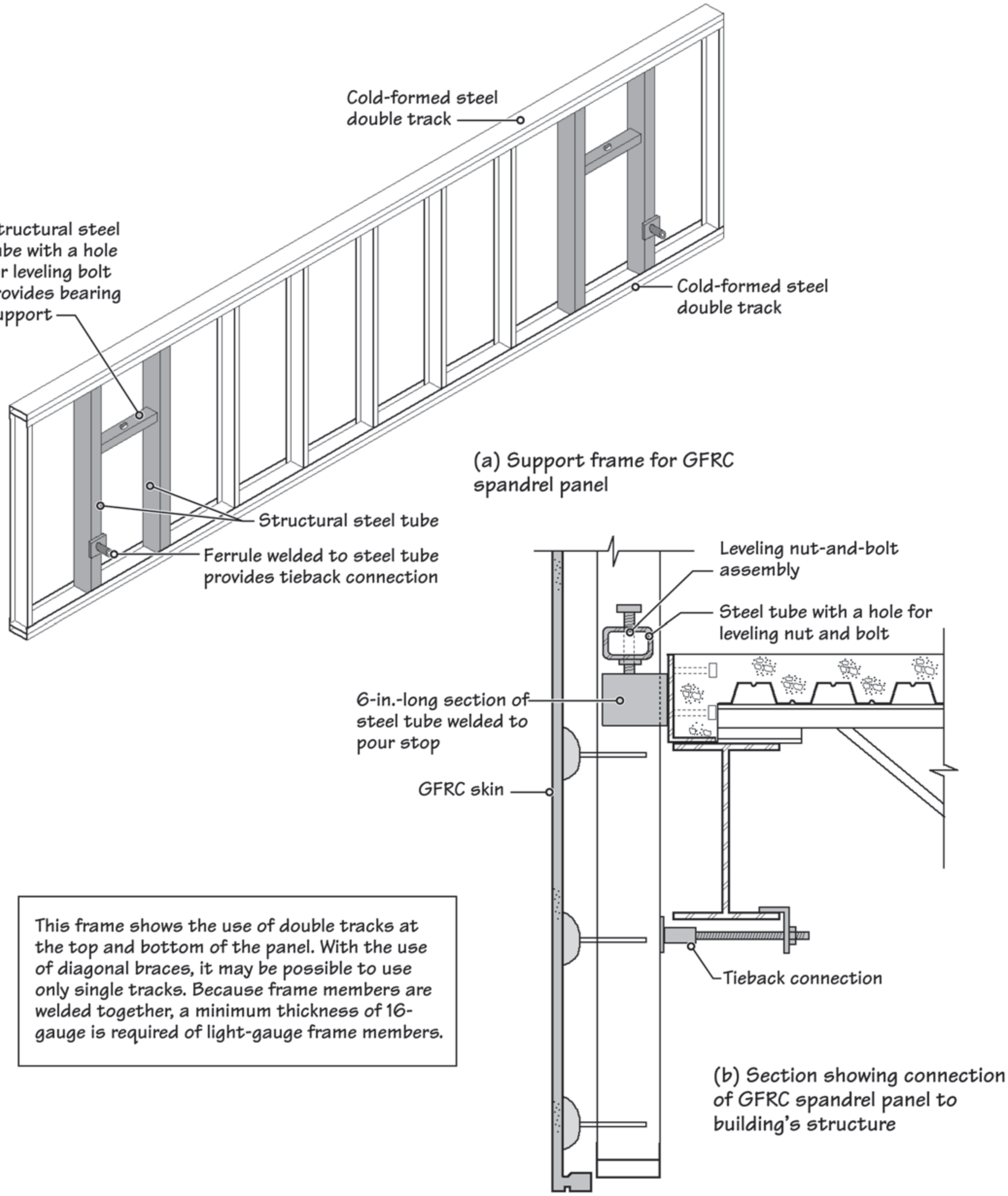
This frame shows the use of double tracks at the top and bottom of the panel. With the use of diagonal braces, it may be possible to use only single tracks. Because frame members are welded together, a minimum thickness of 16-gauge is required of light-gauge frame members.

(a) Support frame for GFRC spandrel panel

(b) Section showing connection of GFRC spandrel panel to building's structure

FIGURE 28.58 Schematic details of bearing and tieback connections in a GFRC spandrel panel (also see Figures 28.59 and 28.60).

Figure 28.60 shows a typical GFRC curtain wall detail. Because the GFRC skin is thin, some form of water drainage system from behind the skin should be incorporated in the panels. Additionally, the space between the GFRC skin and the panel frame should be freely ventilated to prevent the condensation of water vapor. This is generally not a requirement in precast concrete curtain walls. A two-way joint sealant system may be used at panel junctions similar to that for PC curtain walls.


Cold-formed steel double track
Structural steel tube with a hole for leveling bolt provides bearing support
Cold-formed steel double track
Structural steel tube
Ferrule welded to steel tube provides tieback connection
Leveling nut-and-bolt assembly
Steel tube with a hole for leveling nut and bolt
6-in.-long section of steel tube welded to pour stop
GFRC skin
Tieback connection

(a) Support frame for GFRC spandrel panel

(b) Section showing connection of GFRC spandrel panel to building's structure

This frame shows the use of double tracks at the top and bottom of the panel. With the use of diagonal braces, it may be possible to use only single tracks. Because frame members are welded together, a minimum thickness of 16-gauge is required of light-gauge frame members.

FIGURE 28.59 Schematic details of bearing supports and tieback connections in a spandrel GFRC panel (also see Figures 28.58 and 28.60).

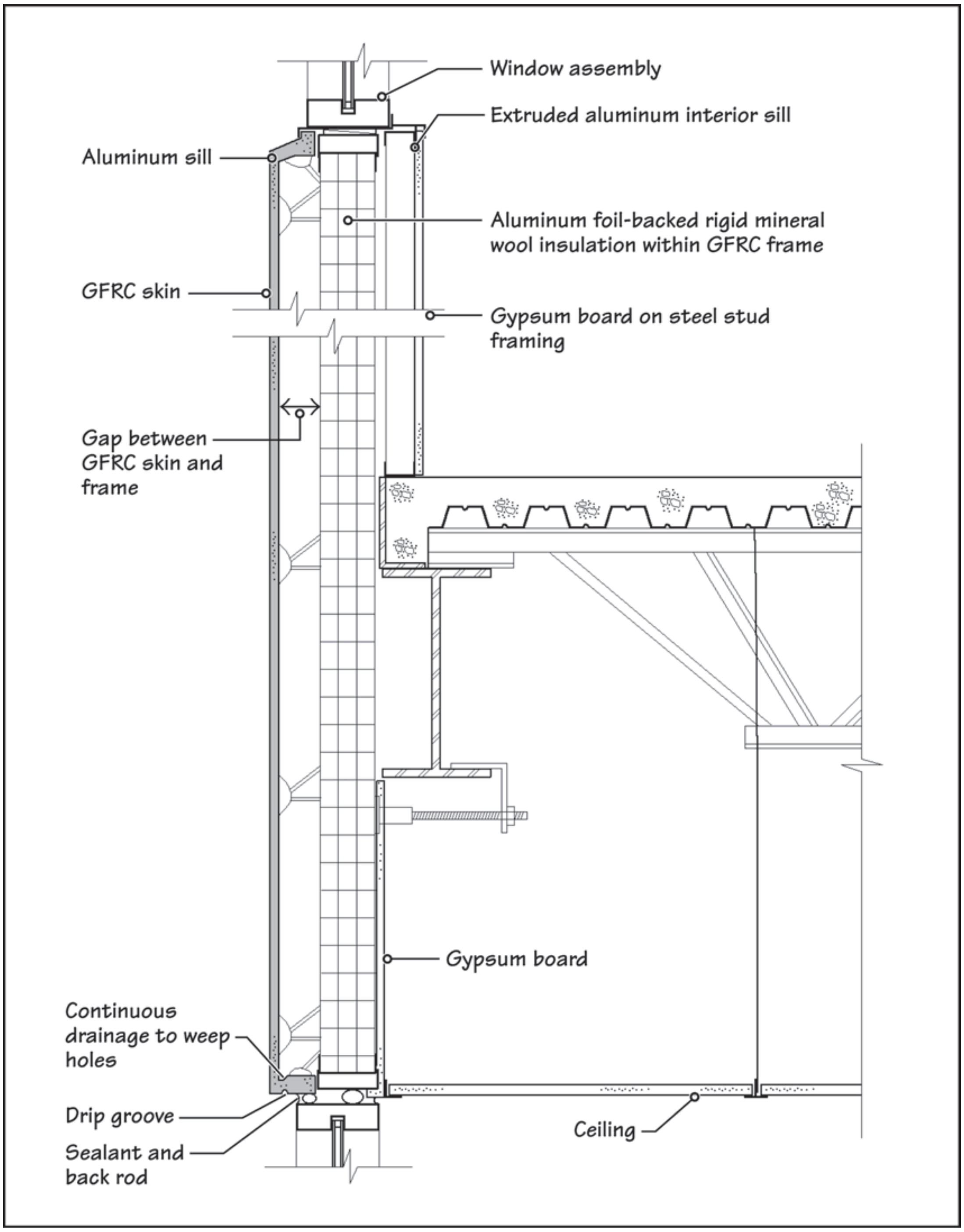

Window assembly
Extruded aluminum interior sill
Aluminum sill
Aluminum foil-backed rigid mineral wool insulation within GFRC frame
GFRC skin
Gypsum board on steel stud framing
Gap between GFRC skin and frame
Gypsum board
Continuous drainage to weep holes
Drip groove
Sealant and back rod
Ceiling

FIGURE 28.60 Schematic detail of an exterior wall with GFRC spandrel panels and ribbon windows.

PRACTICE **QUIZ**

Each question has only one correct answer. Select the choice that best answers the question.

30. The term *GFRC* is an acronym for
a. glass fiber–reinforced concrete.
b. glass fiber–reinforced cement.
c. glass fiber–restrained concrete.
d. glass fiber–restrained cement.
e. none of the above.

31. A GFRC curtain wall panel consists of
a. a GFRC skin.
b. a cold-formed steel frame.
c. anchors.
d. all of the above.
e. (a) and (b).

32. The GFRC skin is typically
a. 2 in. to 3 in. thick.
b. $1\frac{1}{2}$ in. to $2\frac{1}{2}$ in. thick.
c. 1 in. to 2 in. thick.
d. $\frac{1}{2}$ in. to $\frac{3}{4}$ in. thick.
e. none of the above.

33. The glass fibers used in the GFRC skin are referred to as *AR fibers*. The term *AR* is an acronym for
a. alkali resistant.
b. acid resistant.
c. alumina resistant.
d. aluminum reinforced.
e. none of the above.

34. The anchors used in GFRC panels are typically
a. two-piece anchors.
b. one-piece anchors.
c. either (a) or (b), depending on the thickness of the GFRC skin.
d. either (a) or (b), depending on the lateral loads to which the panel is subjected.
e. none of the above.

35. The GFRC skin is obtained by
a. casting the GFRC mix in a mold similar to casting a precast concrete member.
b. applying the mix with a trowel.
c. spraying the mix over a mold.
d. any of the above, depending on the panel fabricator.

36. GFRC curtain wall panels are generally lighter than the corresponding precast concrete curtain wall panels.
a. True
b. False

REVIEW QUESTIONS

1. Using sketches and notes, explain the adjustability requirements of anchors used in a brick veneer wall assembly.
2. Using sketches and notes, explain the functions of a shelf angle and a lintel angle in a brick veneer assembly.
3. With the help of sketches and notes, explain various ways in which weep holes can be provided in a brick veneer assembly.
4. Discuss the pros and cons of using a CMU backup wall versus a steel stud backup wall in a brick veneer wall assembly.
5. With the help of sketches and notes, explain the support system of a precast concrete curtain wall panel.
6. Using sketches, explain the commonly used shapes of precast concrete wall panels.
7. With the help of a sketch, explain the two-stage joint seal in precast concrete wall panels. What are its advantages over a single-stage joint seal?
8. Using sketches and notes, explain the anatomy of an insulated sandwich precast concrete curtain wall panel.
9. Using a sketch, explain the purpose of a (a) bonding pad and (b) flex anchor in a GFRC panel.

CHAPTER 29

Exterior Wall Cladding–III (Stucco, Adhered Veneer, EIFS, Natural Stone, and Insulated Metal Panels)

CHAPTER OUTLINE

29.1 PORTLAND CEMENT PLASTER (STUCCO) BASICS

29.2 STUCCO ON STEEL- OR WOOD-STUD WALLS

29.3 STUCCO ON MASONRY AND CONCRETE SUBSTRATES

29.4 LIMITATIONS AND ADVANTAGES OF STUCCO

29.5 ADHERED MASONRY VENEER

29.6 EXTERIOR INSULATION AND FINISH SYSTEM (EIFS) BASICS

29.7 APPLICATION OF POLYMER-BASED EIFS

29.8 IMPACT-RESISTANT AND DRAINABLE EIFS

29.9 EXTERIOR CLADDING WITH DIMENSION STONE

29.10 FIELD INSTALLATION OF STONE—STANDARD-SET METHOD

29.11 FIELD INSTALLATION OF STONE—VERTICAL CHANNEL METHOD

29.12 THIN STONE CLADDING

29.13 INSULATED METAL PANELS

This chapter continues the discussion of exterior wall cladding systems. Topics discussed in this chapter are Portland cement plaster (stucco), adhered masonry veneer, exterior insulation and finish systems (EIFS), stone cladding, and insulated metal wall panels.

29.1 PORTLAND CEMENT PLASTER (STUCCO) BASICS

Plaster has been used for centuries as an exterior and interior wall and ceiling finish. Apart from rendering the wall and ceiling surfaces smooth and paintable, plastering makes them more resistant to water and air infiltration and increases sound insulation and resistance to fire.

A plaster mix is similar to a masonry mortar mix and consists of cementitious material(s), sand, and water. In some plasters, a fibrous admixture is also used. Prior to the discovery of Portland cement and gypsum, lime was the only cementitious material available for plaster. In contemporary construction, gypsum and Portland cement are the primary cementitious materials. Because gypsum is not a hydraulic cement (i.e., it will dissolve in water), gypsum plaster is suitable only for interior applications not subjected to high humidity levels or wetting.

As noted in Chapter 16, gypsum plaster has largely been replaced by (prefabricated) gypsum boards. Therefore, we limit the discussion to Portland cement plaster. Unlike gypsum plaster, Portland cement plaster can be used on both interior and exterior surfaces.

The predominant use of Portland cement plaster in contemporary buildings is as an exterior wall finish—the topic of discussion in this chapter. Its use as an interior finish is limited to situations where high humidity levels or wetting of the plastered surfaces occur, such as in saunas, public shower rooms, and commercial kitchens. In most parts of the United States, exterior Portland cement plaster is referred to as *stucco*.

Although stucco can be applied on adobe walls, it is more commonly used on:

- Cold-formed steel stud walls
- Wood stud walls
- Masonry walls
- Concrete walls

Because stucco is a Portland cement–based material, the application of stucco requires appropriate temperature conditions. Generally, stucco should be applied if the ambient air temperature is at least 40°F (5°C) and rising.

MIX COMPOSITION FOR STUCCO COATS

Stucco is typically applied sequentially in two coats over a wall, called the *base coat* and the *finish coat*. In some situations, the base coat is applied in two layers, referred to as the *scratch coat* and the *brown coat*. The ingredients of the base coat are Portland cement, lime, sand, and water.

Portland cement is the glue that bonds all constituents of the mix, which eventually cure into a strong and rigid surface. Lime imparts plasticity and cohesiveness to the mix. Plasticity implies that the mix can be spread easily, and cohesiveness implies that the mix will hold and not sag on a vertical surface during application.

Generally, Portland cement and lime for the base coat are factory blended into one bag, Figure 29.1(a). The bag ingredients are site mixed with sand and water in a mixer. Like the base coat, the finish coat is factory blended into one bag, Figure 29.1(b). Color is integral to the finish coat mix. The finish coat does not require the addition of sand; hence, water is the only additional material needed to prepare the finish coat for application. Although a one-bag finish coat helps to provide consistent quality from batch to batch, it is necessary that it be applied continuously, with interruptions only at the control joints or expansion joints.

Two types of factory-blended mixes for the finish coat are available:

- Portland cement–based mix
- Acrylic polymer–based mix

The use of an acrylic polymer–based finish coat is more common because it is more flexible, reduces cracking of the stucco surface, and provides consistent and relatively nonfading colors. However, a Portland cement–based finish coat is more breathable (vapor-permeable) than a polymer-based finish so that any moisture trapped within or behind the stucco dries out faster.

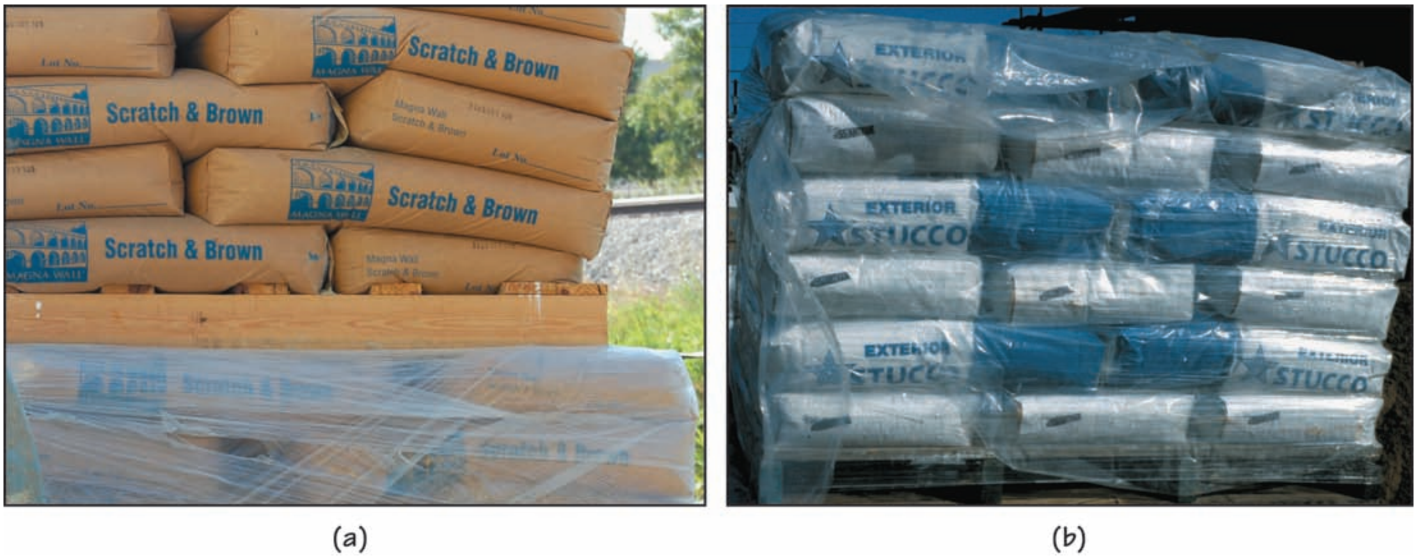
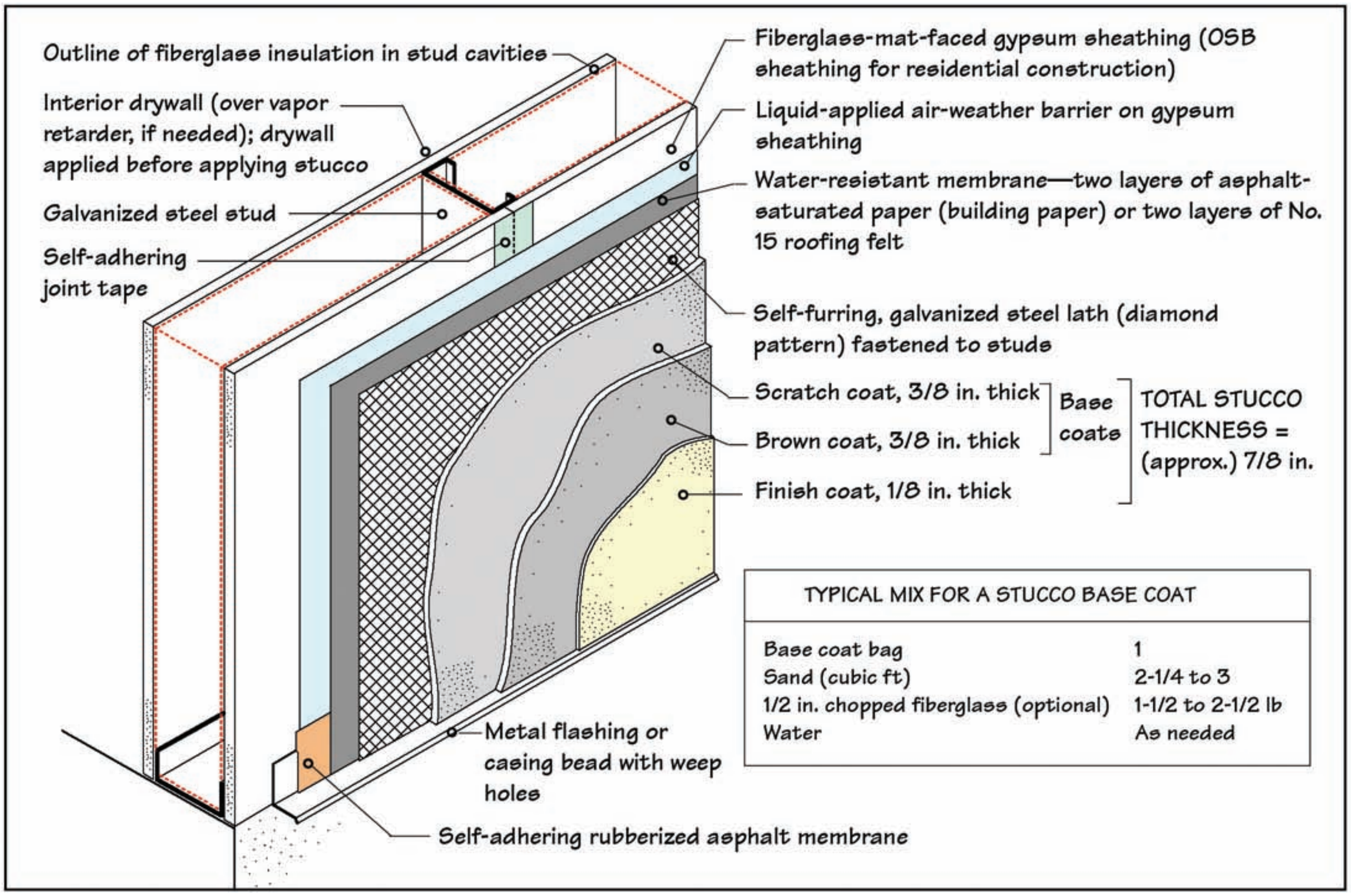


FIGURE 29.1 **(a)** Bags containing base coat material (Portland cement and lime blended together). The bags are emptied in a mixer, to which sand and water are added to obtain the stucco base coat mix. **(b)** Bags containing finish coat material, which requires only the addition of water to obtain the finish coat mix.


Outline of fiberglass insulation in stud cavities
Interior drywall (over vapor retarder, if needed); drywall applied before applying stucco
Galvanized steel stud
Self-adhering joint tape
Fiberglass-mat-faced gypsum sheathing (OSB sheathing for residential construction)
Liquid-applied air-weather barrier on gypsum sheathing
Water-resistant membrane—two layers of asphalt-saturated paper (building paper) or two layers of No. 15 roofing felt
Self-furring, galvanized steel lath (diamond pattern) fastened to studs
Scratch coat, 3/8 in. thick
Brown coat, 3/8 in. thick
Base coats
Finish coat, 1/8 in. thick
TOTAL STUCCO THICKNESS = (approx.) 7/8 in.
Metal flashing or casing bead with weep holes
Self-adhering rubberized asphalt membrane

TYPICAL MIX FOR A STUCCO BASE COAT

Base coat bag	1
Sand (cubic ft)	2-1/4 to 3
1/2 in. chopped fiberglass (optional)	1-1/2 to 2-1/2 lb
Water	As needed

FIGURE 29.2 Anatomy of a steel- or wood-stud wall with Portland cement stucco finish.

NOTE

Building Paper or Roofing Felt Backing for Stucco—The Drainage Plane

The building paper or the roofing felt absorbs a certain amount of water during the application of stucco. As the paper (or felt) and stucco dry, the paper (or felt) wrinkles and the stucco shrinks, leaving small vertical drainage channels behind the stucco. Although the drainage channels are small (unlike an air space in a drainage wall), they help keep the stucco wall dry. The multitude of drainage channels are referred to as a *drainage plane*.

A proprietary air-retarder-type backing for stucco is also available that has a specially made crinkled surface, providing a drainage plane similar to the one that develops in a paper- or felt-backed stucco.

29.2 STUCCO ON STEEL- OR WOOD-STUD WALLS

The anatomies of wood and cold-formed steel-frame walls with a stucco finish are essentially identical, as shown in Figure 29.2. Both wall assemblies require an exterior (gypsum, plywood, OSB, or cement board) sheathing, a water-resistant membrane, and a self-furring metal base.

The water-resistant membrane is the second line of defense against water intrusion. The first line of defense is the stucco finish itself. In most projects, two layers of asphalt-saturated building paper or one layer of No. 15 asphalt-saturated roofing felt (see Chapter 33) is used as the water-resistant membrane. It is applied horizontally with laps between sheets.

The metal base generally consists of self-furring galvanized steel lath (diamond pattern), Figure 29.3. The lath is fabricated from steel sheets, which are slit at regular intervals and

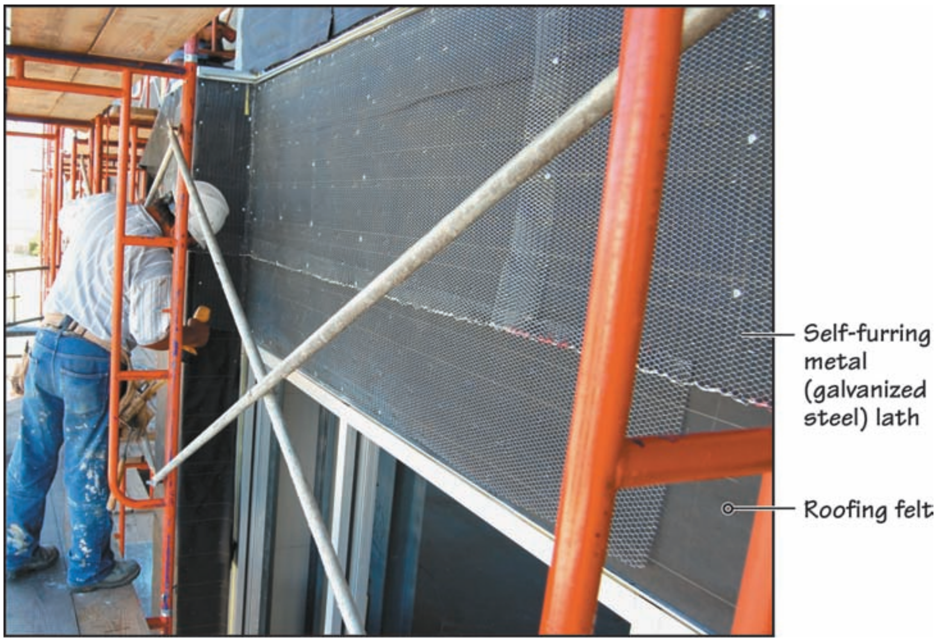

Self-furring metal (galvanized steel) lath
Roofing felt

FIGURE 29.3 A worker fastening self-furring metal lath (diamond pattern) over No. 15 roofing felt.

then stretched. For this reason, the lath is also known as *expanded metal lath*. The lath sheets are finally hot-dip galvanized, as needed.

The lath provides a mechanical key to which the stucco bonds. The self-furring character of the lath is obtained by incorporating dimples or other means in the lath during the stretching process that hold it about $\frac{1}{4}$ in. away from the substrate. Thus, when the stucco coat is applied, the lath is embedded in it, becoming an integral part of the stucco, much like the reinforcing bars in a reinforced-concrete slab.

Self-furring lath is also available with a continuous backing of building paper integral with the lath. This combination increases work efficiency, particularly in large stucco projects.

In a wood-stud wall, the lath is fastened to the studs with large-head nails. In a cold-formed steel-stud wall, the lath is anchored to the studs with self-drilling, self-tapping screws with large (nearly $\frac{1}{2}$-in.-diameter) heads. Because the lath is anchored to the studs, the stucco is structurally engaged to the studs.

APPLICATION OF STUCCO

Figure 29.4 shows the exterior of a building covered with scaffolding in readiness for stucco application. Stucco applied on (wood- or steel-) stud walls generally consists of two coats (a scratch coat and a base coat), each approximately $\frac{3}{4}$ in. thick, and an approximately $\frac{1}{8}$-in.-thick finish coat, giving a total stucco thickness of approximately $\frac{7}{8}$ in.

The ingredients for all coats are mixed in a mixer, which is connected to a pump, Figure 29.5. The mix is delivered to the point of application through a long pipe terminating in a nozzle that sprays the mix, Figure 29.6(a).

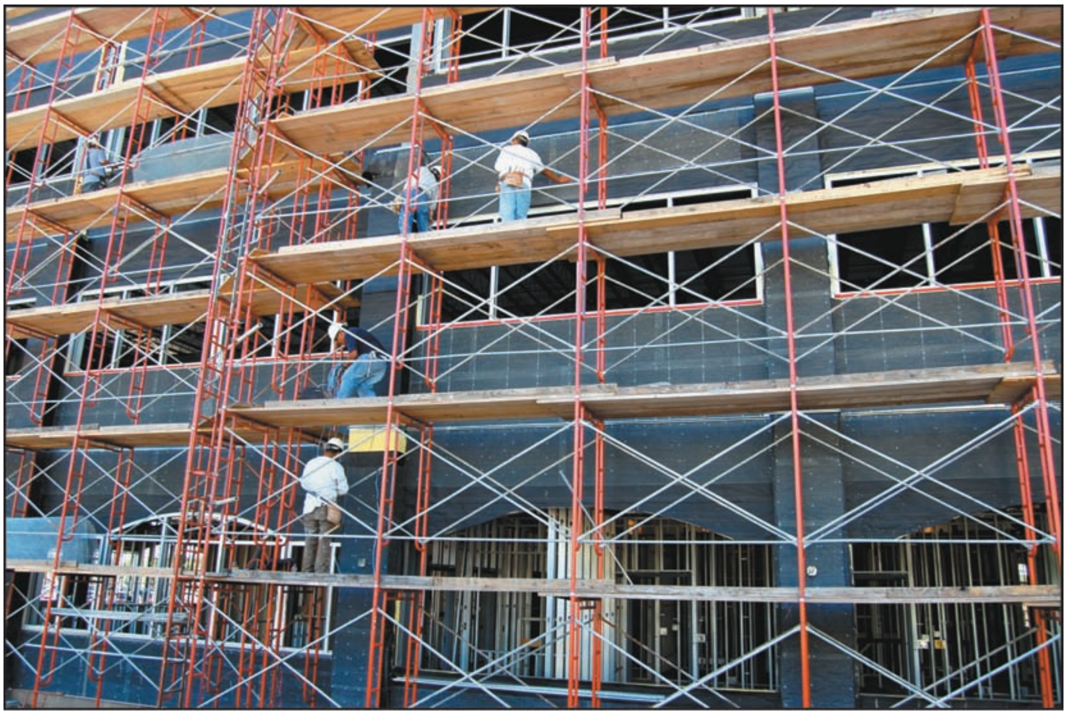


FIGURE 29.4 A five-story building facade covered with scaffolding for the application of stucco.

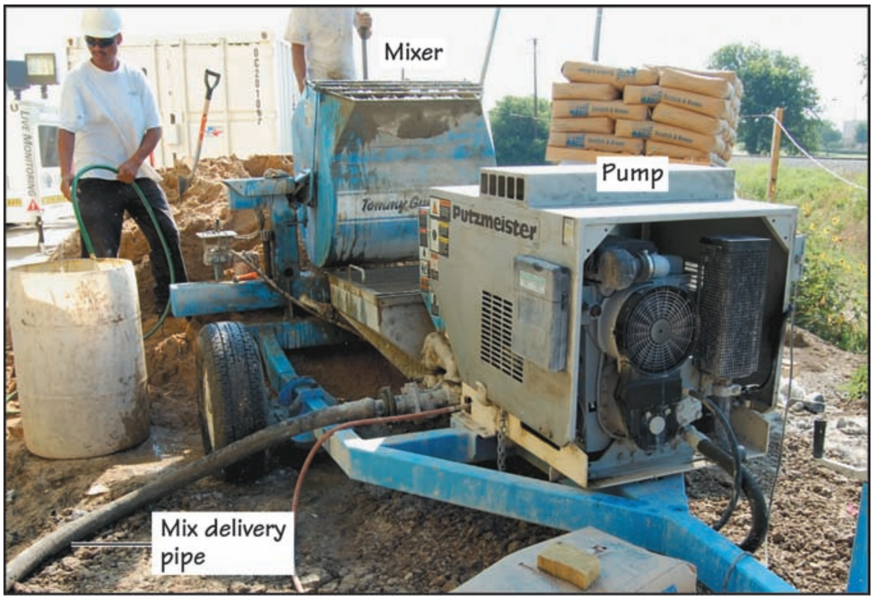
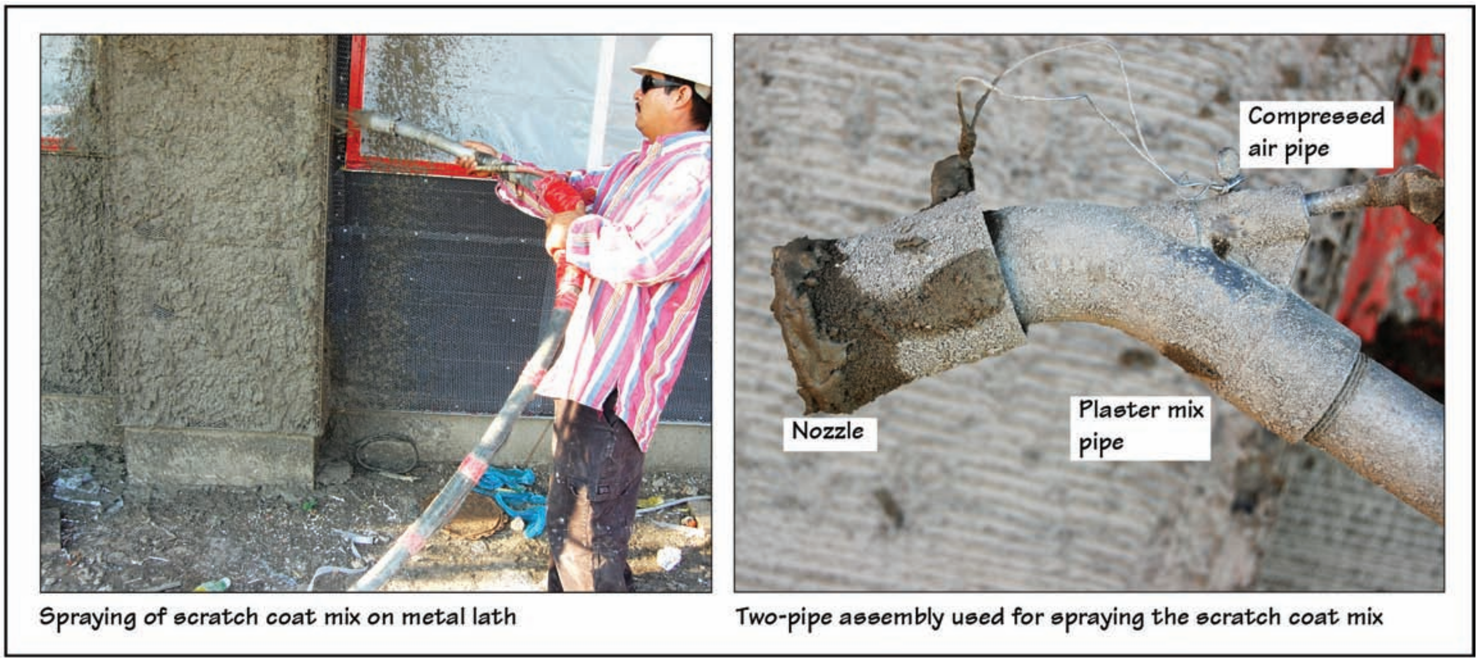


FIGURE 29.5 A stucco mixer and pump. The pump receives the mix from the mixer and delivers it through a pipe to the point of application.



Spraying of scratch coat mix on metal lath

Two-pipe assembly used for spraying the scratch coat mix

FIGURE 29.6(a) Application of Portland cement stucco Step 1: spraying of scratch coat mix on metal lath.

For the scratch coat, the sprayed-on material is troweled with sufficient pressure to squeeze it through the lath so that the lath is embedded completely in the scratch coat, Figure 29.6(b). Generally, one plasterer sprays the mix, and then another plasterer hand trowels the sprayed material. After the troweling operation, the material is scratched (hence the name *scratch coat*). The scratched surface provides a mechanical key for the following brown coat. On a wall (vertical surface), the scratches are horizontal.

The mix for the brown coat is also spray-applied in the same way as the scratch coat. However, the sprayed-on material is brought to an even plane using a wood or metal float, which also densifies the applied material, Figure 29.6(c). After floating, the surface is troweled with a steel trowel, which smoothes the surface further and prepares it for the finish coat.

The time interval between the scratch and brown coats depends on the ambient temperature and humidity conditions. It is important that the scratch coat develop sufficient strength and rigidity to carry the weight of the brown coat without damaging the grooves. At the same time, the scratch coat should not set and dry so much that its bond with the subsequent coat is compromised.

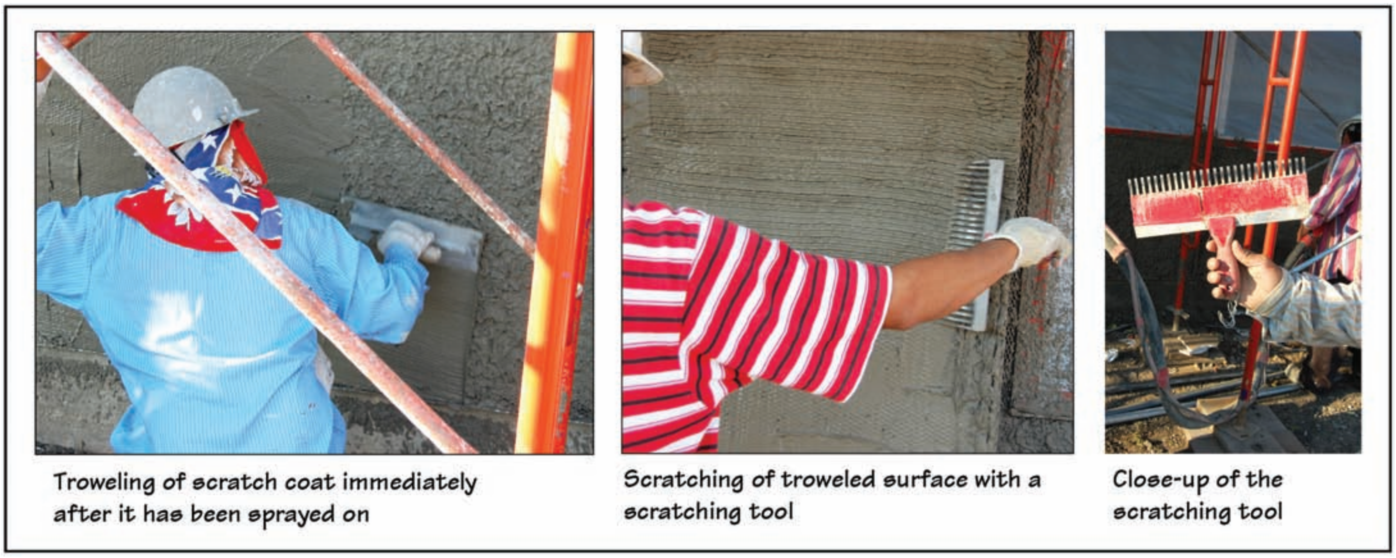
A 24- to 48-h interval between the scratch and brown coats is commonly used in most climates. If a larger interval is used, the scratch coat should be moist cured until the application of the brown coat.

The finish coat is obviously the most important component of the stucco finish because it provides the required color and texture. It is generally troweled on, Figure 29.6(d). A time interval of five to seven days is generally required between the brown coat and the finish coat to allow the base coat (scratch and brown) coats to stabilize from shrinkage.

NOTE

Control Joint Locations on Stucco Applied on Wood- or Steel-Stud Walls

- The maximum area between control joints is 144 ft^2.
- The maximum length or width of an area between control joints is 18 ft.
- The length-to-width ratio of an area between control joints should be between 1 and 2.5.

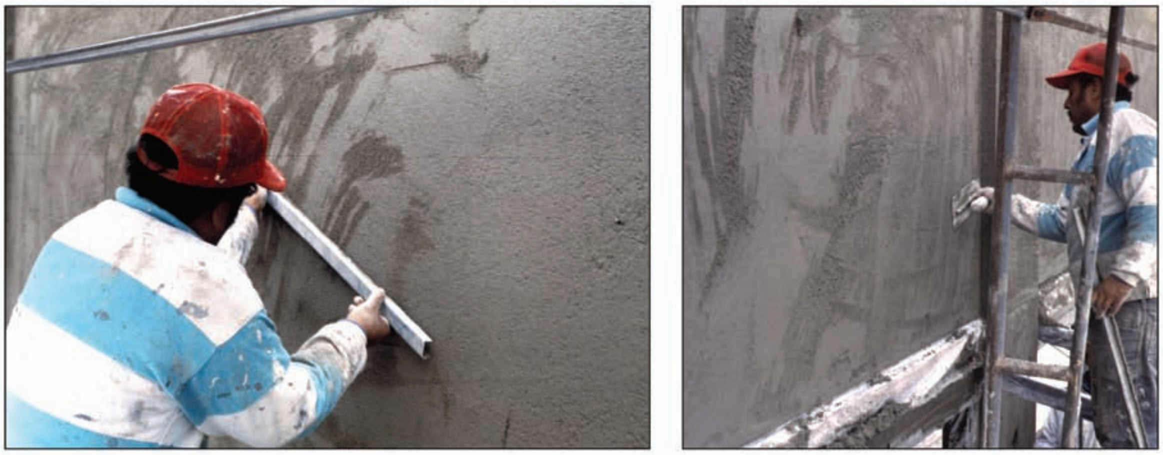


Troweling of scratch coat immediately after it has been sprayed on

Scratching of troweled surface with a scratching tool

Close-up of the scratching tool

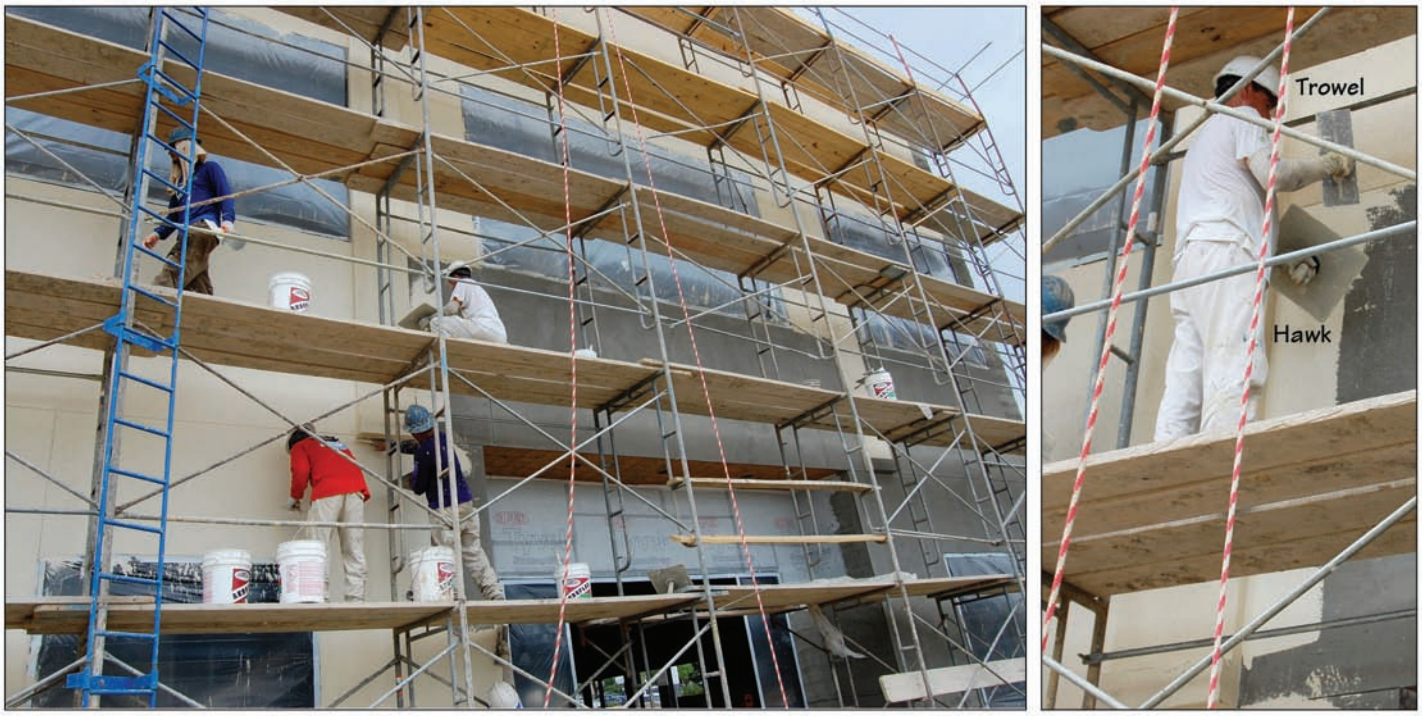
FIGURE 29.6(b) Application of Portland cement stucco Step 2: scratching of the troweled scratch coat.



Brown coat is applied in the same way as the scratch coat, that is, by spraying. It is then floated, as shown.

Troweling of brown coat to obtain a smooth surface

FIGURE 29.6(c) Application of Portland cement stucco Step 3: finishing of the brown coat immediately after it has been spray applied like the scratch coat.



Plasterers applying finish coat (cream color) on stucco brown coat (dark gray in color)

A hawk and a trowel—the tools used for applying the finish coat

FIGURE 29.6(d) Application of Portland cement stucco Step 4: the finish coat, approximately $\frac{1}{8}$ in. thick, is applied using a trowel. The finish coat mix generally consists of a polymer-based material and is supplied by the stucco manufacturer in bags in ready-to-use formulation, as shown in Figure 29.1(b).

Some finish coat manufacturers require two applications of their material. The first application is that of a primer, which prepares the base coat surface to receive the finish coat and improves adhesion between the base coat and the finish coat. The finish coat develops the final stucco color and texture.

CONTROL JOINTS AND EXPANSION JOINTS

Because of the presence of Portland cement, shrinkage is an inherent feature of a stucco surface, which leads to its cracking. Although the cracking of stucco cannot be fully eliminated, it can be controlled by providing closely spaced control joints.

ASTM standards require that the area between control joints in stucco applied on a stud-wall assembly not exceed 144 ft^2, with neither dimension of this area exceeding 18 ft. As far as possible, control joints should also be provided around openings in walls, Figure 29.7.

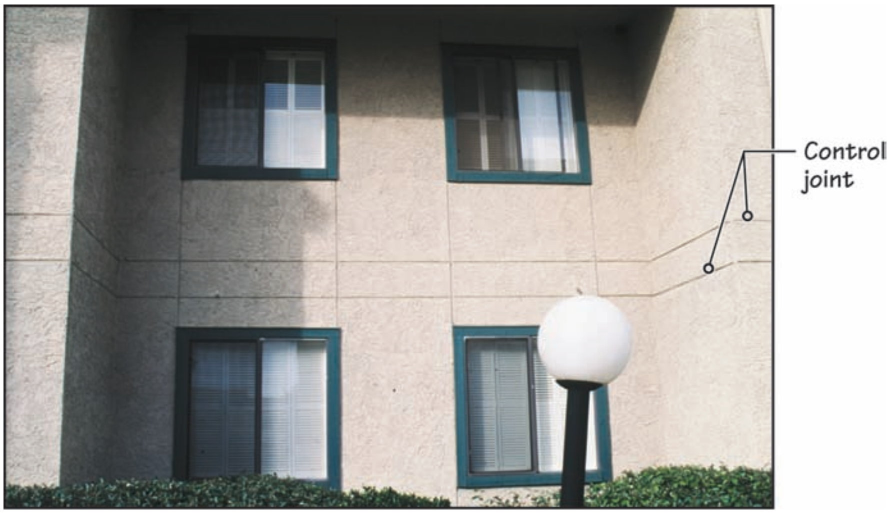

Control
joint

FIGURE 29.7 Control joints on a stucco facade.

In addition to control joints, expansion joints are needed in a stucco finish. Although control joints are a means of controlling the shrinkage of the stucco finish, expansion joints respond to large movements in the building structure. Thus, expansion joints should be provided at each floor level in the exterior wall in a multistory building to absorb the movement in the spandrel beam, Figure 29.8. Expansion joints are also needed where there is a

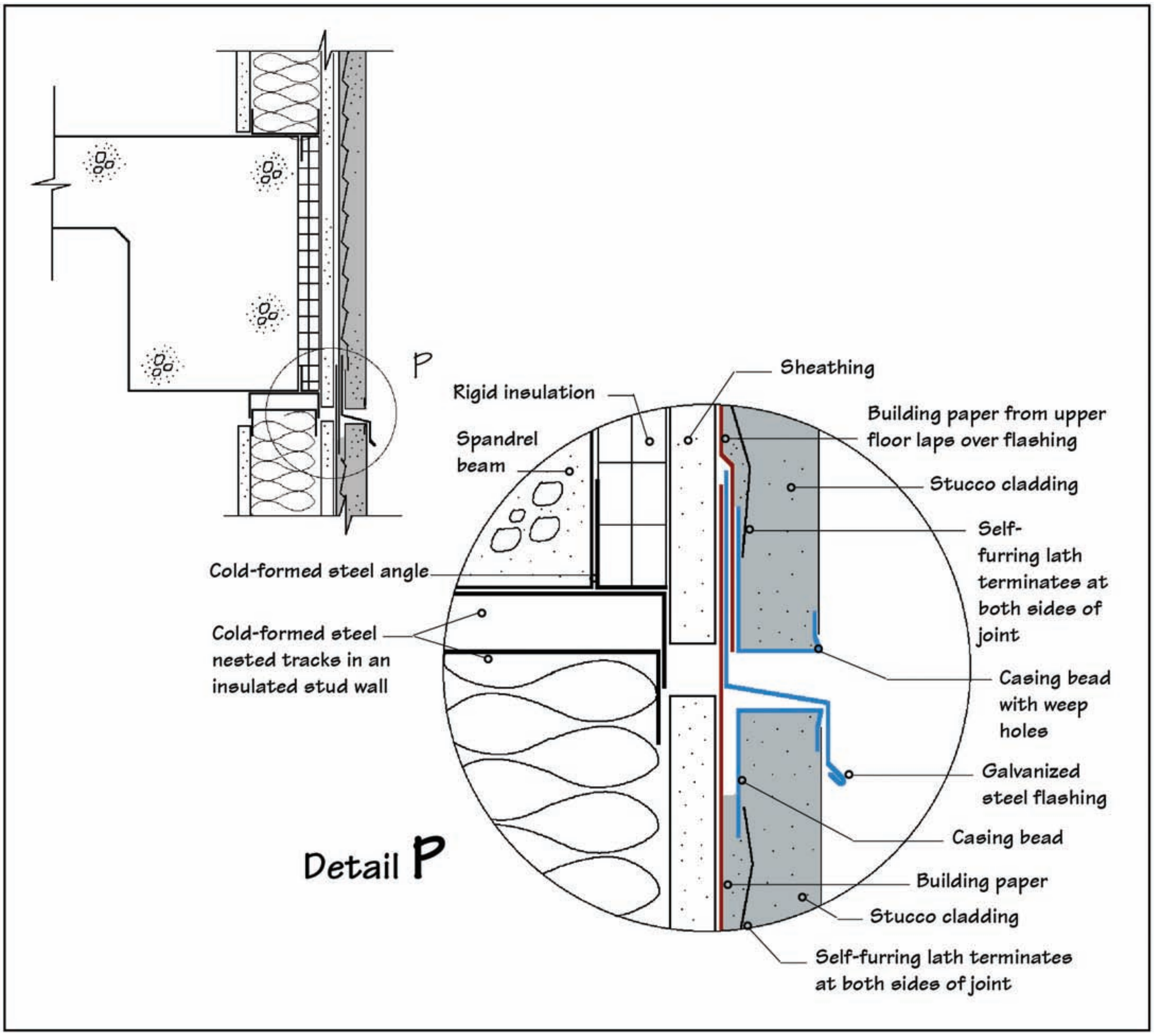

P
Sheathing
Rigid insulation
Spandrel
beam
Building paper from upper
floor laps over flashing
Stucco cladding
Self-
furring lath
terminates at
both sides of
joint
Cold-formed steel angle
Cold-formed steel
nested tracks in an
insulated stud wall
Casing bead
with weep
holes
Galvanized
steel flashing
Casing bead
Detail P
Building paper
Stucco cladding
Self-furring lath terminates
at both sides of joint

FIGURE 29.8 A typical horizontal expansion joint detail in a stucco-clad exterior stud wall. For a vertical expansion joint, a two-piece expansion joint accessory may be used; see Figure 29.10(c).

major change in building elevation or where a stucco-finished wall abuts a wall made of a different material.

If the movement of the spandrel beam is not transferred to the wall, the wall needs only control joints. This is shown in Figure 29.9, which illustrates the detailing of a typical control joint and the termination of stucco at the foundation level.

Control joints and expansion joints are constructed using accessories, Figure 29.10. The flanges of joint accessories consist of expanded metal or a slotted material so that they can integrate with the lath and be fastened to the studs in the same way as the lath.

A control joint accessory consists of a single piece, whereas an expansion joint is a two-piece accessory. In the case of an expansion joint, the lath must terminate on both sides of the joint. The lath should, however, be continuous under a control joint.

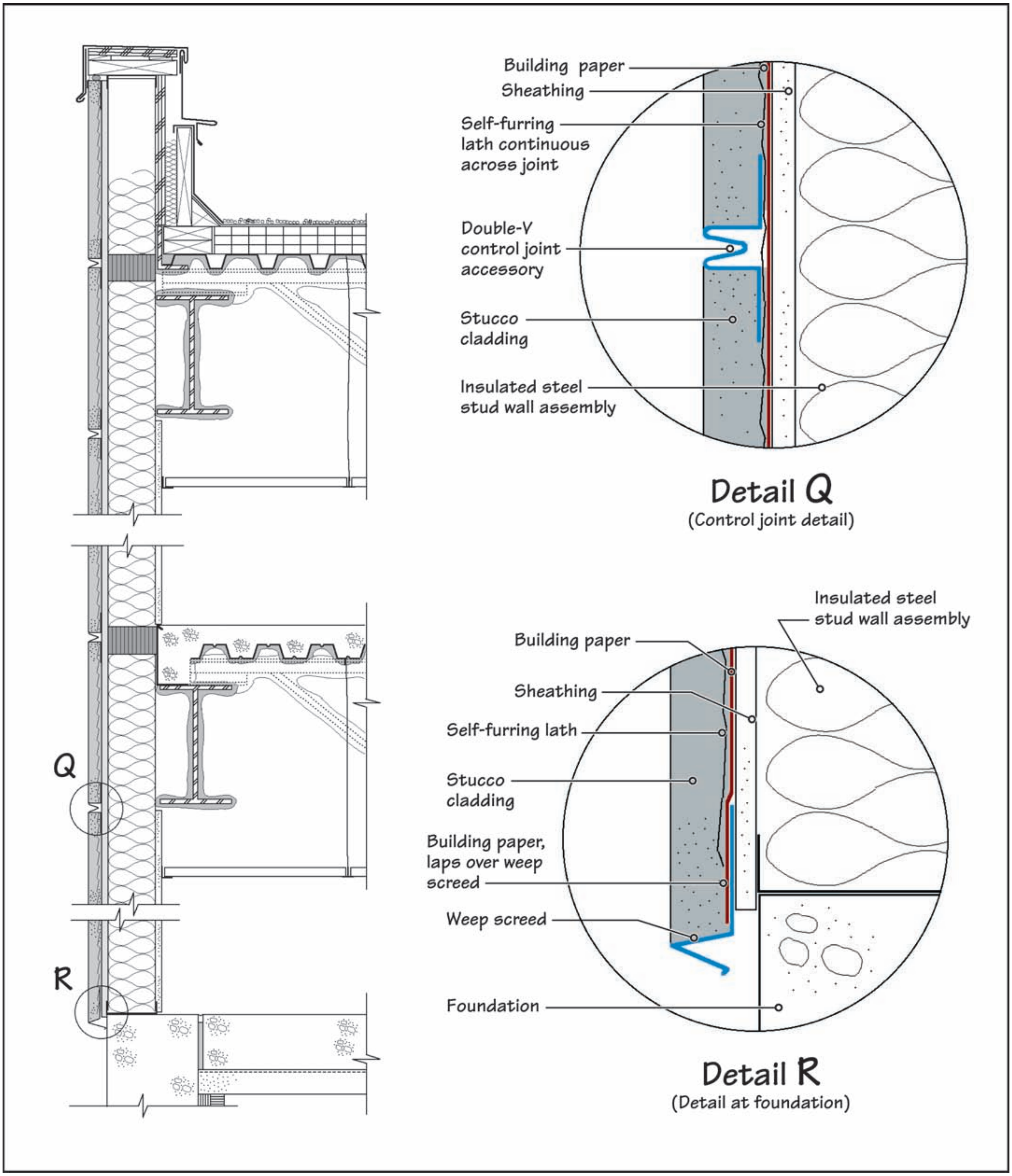

Building paper
Sheathing
Self-furring lath continuous across joint
Double-V control joint accessory
Stucco cladding
Insulated steel stud wall assembly
Detail Q
(Control joint detail)
Q
R
Insulated steel stud wall assembly
Building paper
Sheathing
Self-furring lath
Stucco cladding
Building paper, laps over weep screed
Weep screed
Foundation
Detail R
(Detail at foundation)

FIGURE 29.9 A typical wall section and corresponding details of a low-rise, stucco-clad steel-frame building.

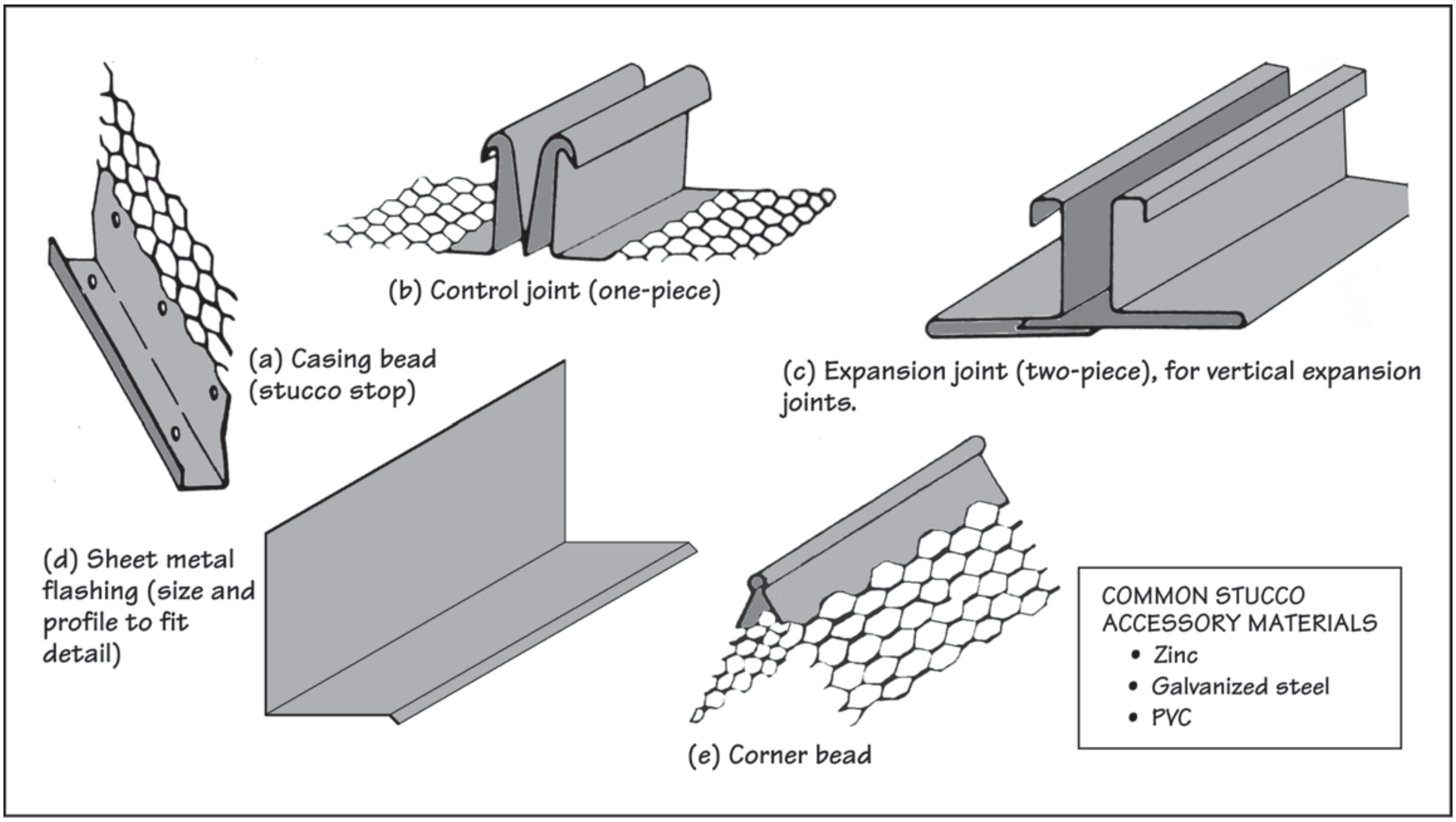

(b) Control joint (one-piece)
(a) Casing bead (stucco stop)
(c) Expansion joint (two-piece), for vertical expansion joints.
(d) Sheet metal flashing (size and profile to fit detail)
(e) Corner bead
COMMON STUCCO ACCESSORY MATERIALS
• Zinc
• Galvanized steel
• PVC

FIGURE 29.10 Commonly used accessories and trims for stucco.

Apart from the control and expansion joint accessories, several other accessories and trims, such as casing beads, corner beads, and flashing, are required in a typical stucco project. A casing bead is used at the terminal edge of a stucco surface. Therefore, it is also referred to as a *stucco stop*.

An exterior corner bead provides a straight vertical or horizontal intersection between two surfaces. It also guards against chipping at corners from impact and establishes the thickness of the stucco finish. An interior corner bead is generally not needed with stucco.

The materials used for joint accessories and trims are zinc, galvanized steel, and PVC. In a highly corrosive environment, the use of zinc or PVC should be considered, depending on the local experience. Where accessories abut, the joints at the ends of two lengths or their intersections should be sealed with exterior-grade sealant.

RIGIDITY OF THE STUD WALL ASSEMBLY

Because a fully cured stucco surface is relatively thin ($\frac{7}{8}$ in.) and brittle, it is important that the backup wall assembly be sufficiently rigid. A flexible assembly will aggravate cracking, leading to rapid deterioration of the wall from water penetration, freeze-thaw damage, and so on.

Building codes and standards require that the deflection of wood- and steel-stud-wall assemblies clad with stucco be controlled to a maximum of span divided by 360 (L/360). More stringent deflection-design criterion (e.g., maximum deflection not to exceed L/420 or even L/480) should be considered for a better-performing stucco wall.

ONE-COAT STUCCO

Several manufacturers have developed a one-coat stucco in which the traditional two base coats (scratch coat and brown coat) are replaced by one base coat. The mix for the base coat, which is proprietary to the manufacturer, includes glass fibers in addition to Portland cement and lime. Sand and water are the only ingredients required to prepare the base coat material.

The base coat for one-coat stucco is generally $\frac{1}{2}$ in. thick and is applied on the lath the same way as the scratch coat but is finished smooth, like the brown coat. A thicker base coat may be needed to meet the fire-resistance rating, as required by the applicable building code. The finish coat is applied on one-coat stucco the same way as on the traditional two-coat stucco.

One-coat stucco reduces labor and time. The glass fibers in the base coat help reduce cracking by increasing its flexural strength and impact resistance.

NOTE

Deflection of Stud-Wall Assemblies

The deflection of stud walls that receive stucco finish should not exceed span divided by 360, that is, L/360 caused by lateral loads. Here, L is the vertical span of studs. For steel studs, L is generally the distance between the bottom track and the top track in the assembly.

Steel-stud manufacturers provide tables for the selection of their studs to conform to the deflection criteria. See Section 28.4 for the corresponding deflection criterion for brick veneer backed by steel studs.

For wood studs, L refers to the distance between the bottom plate and the top plate in the wall assembly.

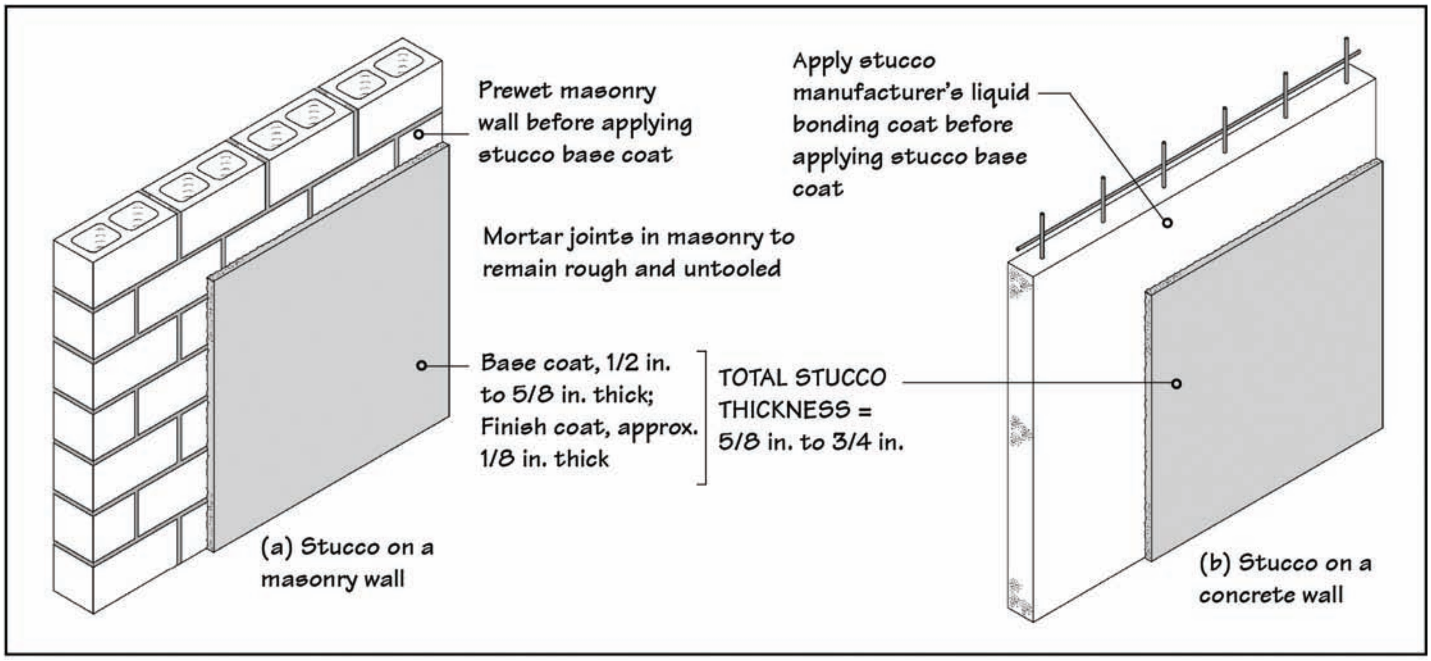

Prewet masonry wall before applying stucco base coat
Mortar joints in masonry to remain rough and untooled
Base coat, 1/2 in. to 5/8 in. thick; Finish coat, approx. 1/8 in. thick
TOTAL STUCCO THICKNESS = 5/8 in. to 3/4 in.
Apply stucco manufacturer's liquid bonding coat before applying stucco base coat
(a) Stucco on a masonry wall
(b) Stucco on a concrete wall

FIGURE 29.11 Anatomy of a stucco-clad **(a)** masonry wall and **(b)** concrete wall.

29.3 STUCCO ON MASONRY AND CONCRETE SUBSTRATES

Masonry is an excellent substrate for stucco because it is far more rigid than a stud wall. Additionally, the surface roughness and porosity of masonry yield a good bond for the stucco finish. Therefore, stucco applied on a masonry wall does not need lath. (Remember that a self-furring lath is required on a stud wall to develop a surface to which stucco will bond. The bond between stucco and concrete masonry is particularly strong because both are Portland cement–based materials.)

Stucco applied on a masonry wall usually consists of two coats (a base coat to smooth any irregularities on the wall's surface and a finish coat) with a total thickness of $\frac{5}{8}$ in. to $\frac{3}{4}$ in., Figure 29.11. To retain the natural roughness of masonry, the mortar joints in masonry are left flush, that is, they are not tooled. Obviously, the masonry surface must be clean and free from defects that may compromise the bond between stucco and masonry.

Because masonry is porous, it may suck water from the mix, leaving insufficient water in stucco. Therefore, a masonry surface may need prewetting before applying the base coat.

A concrete wall is neither as absorptive nor as rough as a masonry wall. Therefore, light sand blasting followed by application of a liquid bonding coat is generally required on a concrete wall, as recommended by the stucco manufacturer. The total thickness of stucco on a concrete wall is nearly the same as on a masonry wall.

JOINTS IN STUCCO-FINISHED MASONRY AND CONCRETE WALLS

Because masonry and concrete walls are more rigid than wood- or steel-stud walls, the control joints in stucco applied on them can be spaced farther apart. The recommended maximum area of a stucco panel between control joints on masonry or concrete substrates is 250 ft^2.

As far as possible, control joints and expansion joints in stucco should be in the same locations as the corresponding joints in substrate masonry or concrete. The control joints and other accessories are fastened to masonry or concrete using masonry or concrete nails.

NOTE

Control Joint Locations on Stucco Applied on Masonry or Concrete Walls

- Maximum area between control joints = 250 ft^2.
- Other requirements are the same as for stud walls.

29.4 LIMITATIONS AND ADVANTAGES OF STUCCO

A stucco-clad masonry or concrete wall is a barrier wall (see Chapter 27). It does not have any means of draining rainwater out of the assembly should rainwater permeate through the stucco. A stucco-clad steel- or wood-stud framed wall, on the other hand, is not a barrier wall.

Although the anatomy of a stucco-clad framed wall does not qualify as a drainage wall, water penetration tests have indicated that if water intrudes through stucco cladding under a long spell of wind-driven rain, it is able to drain out from over the water-resistant barrier behind stucco (i.e., through the *drainage plane*).

The drainage plane is formed because the water-resistive barrier (building paper or roofing felt) crinkles when it becomes wet, forming small vertical grooves to let the rainwater drain. Following on these lines a manufacturer has developed a synthetic membrane, called *stucco wrap* that can be used as a substitute for the building paper or roofing felt, Figure 29.12. However, despite the existence of the drainage plane, good workmanship, rigidity of the substrate, and use of control joints, expansion joints, and sealants are essential for a well-performing stucco assembly, particularly in wet climates.

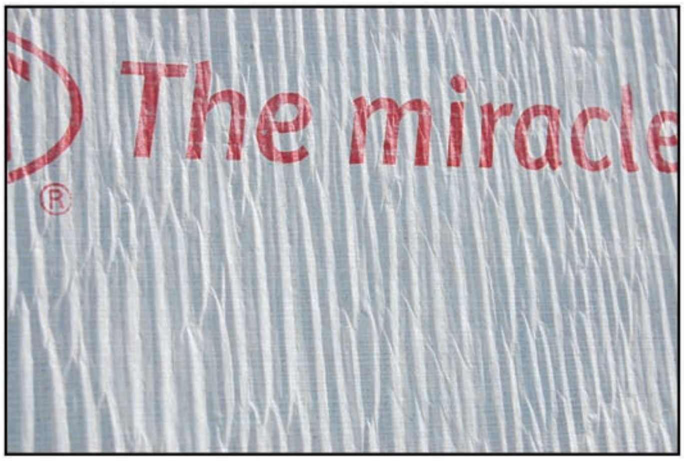


FIGURE 29.12 A close-up of a proprietary water-resistive membrane used as replacement for asphalt-saturated (building) paper or roofing felt. Called *stucco wrap* by the manufacturer, it consists of a synthetic membrane whose surface is crinkled with vertical grooves to form a drainage plane behind the stucco. The crinkling of the membrane is similar to what occurs naturally in building paper or roofing felt as they get wet from rainwater breaching through the stucco.

Additionally, because stucco is a Portland cement–based material, it is a breathable surface. Should water permeate the stucco, it will begin to evaporate as soon as the rain stops and the wall begins to dry. (With an acrylic polymer–based finish coat, the evaporation of water is a little slower but exists all the same.)

Although its relative thinness and lightweight may present some challenges in keeping a stucco-clad wall dry in wet regions, these properties are advantageous in seismic zones. Remember, from Section 3.7, that the earthquake load on a building component is directly related to its dead load. Consequently, a stucco-finished wall is subjected to a smaller earthquake load than a wall clad with heavier finishes, such as masonry veneer or concrete curtain wall.

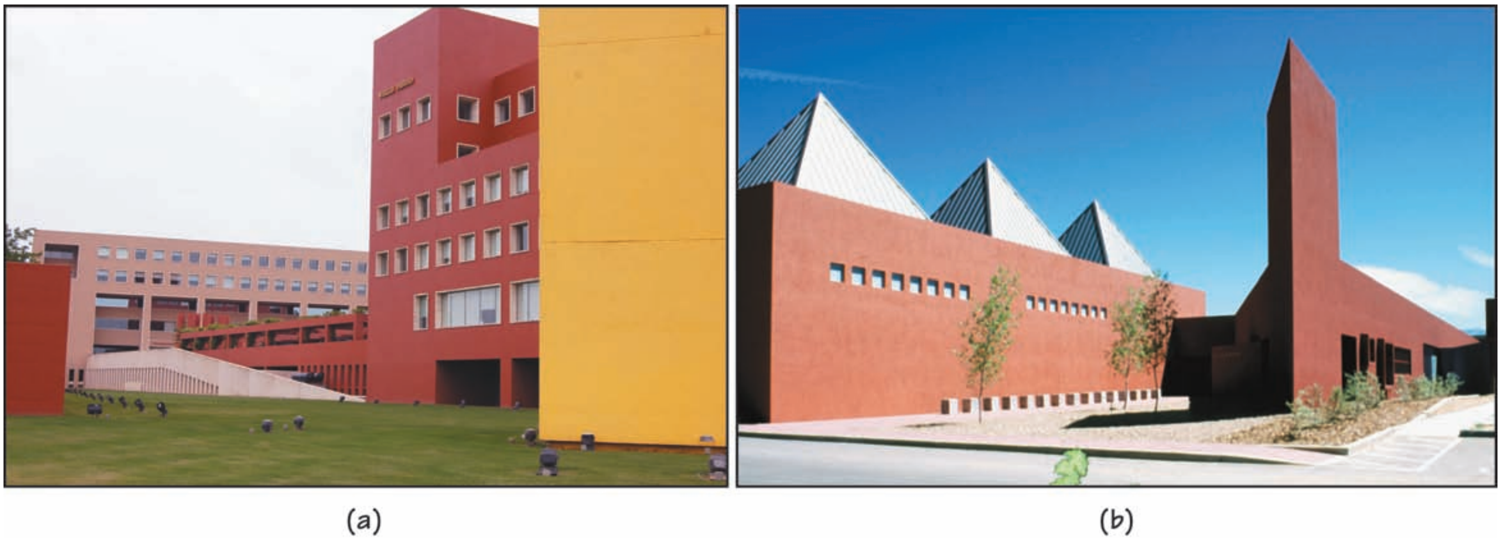
Additionally, because stucco is an adhered finish (in contrast with anchored masonry veneer), it is better able to resist the vibrations caused by an earthquake. A stucco finish is often recommended for use in relatively dry and seismically active regions.

Another advantage of stucco is the clarity of form that results from its use. The variety of colors that are available add to the aesthetic quality of a stucco-finished building. Architects have exploited this attribute of stucco, as shown in the two images of Figure 29.13.

CONTINUOUS INSULATION AND PORTLAND CEMENT STUCCO

One of the major limitations of Portland cement stucco finish is that it does not lend itself to continuous insulation without substantially raising the cost of the assembly (both in the cost of materials and labor). The plastering industry has developed several details [Ref. 29.2] that incorporate continuous insulation, but they have not been accepted widely either because of the cost issues or because they do not fully meet the definition of continuous insulation as provided in the International Energy Conservation Code (IECC).

The detail shown in Figure 29.14 has been used in some low-rise buildings successfully. It uses Z-furring sections fastened to steel studs to accommodate rigid board insulation (extruded polystyrene or polyisocyanurate). The furring sections must be oriented as shown, that is, their upper vertical leg is fastened to the studs, so that their horizontal legs do not trap water, should rainwater breach through the sheathing. The Z-sections are spaced $13\frac{1}{2}$ in. on center because the metal lath is manufactured in 27 in. × 96 in. sheets. The lath is fastened to Z-sections.



(a) (b)

FIGURE 29.13 **(a)** Solana Campus, Westlake, Texas; Architect: Ricardo Legorreta. **(b)** Fine Arts Center, College of Santa Fe, New Mexico; Architect: Ricardo Legorreta.

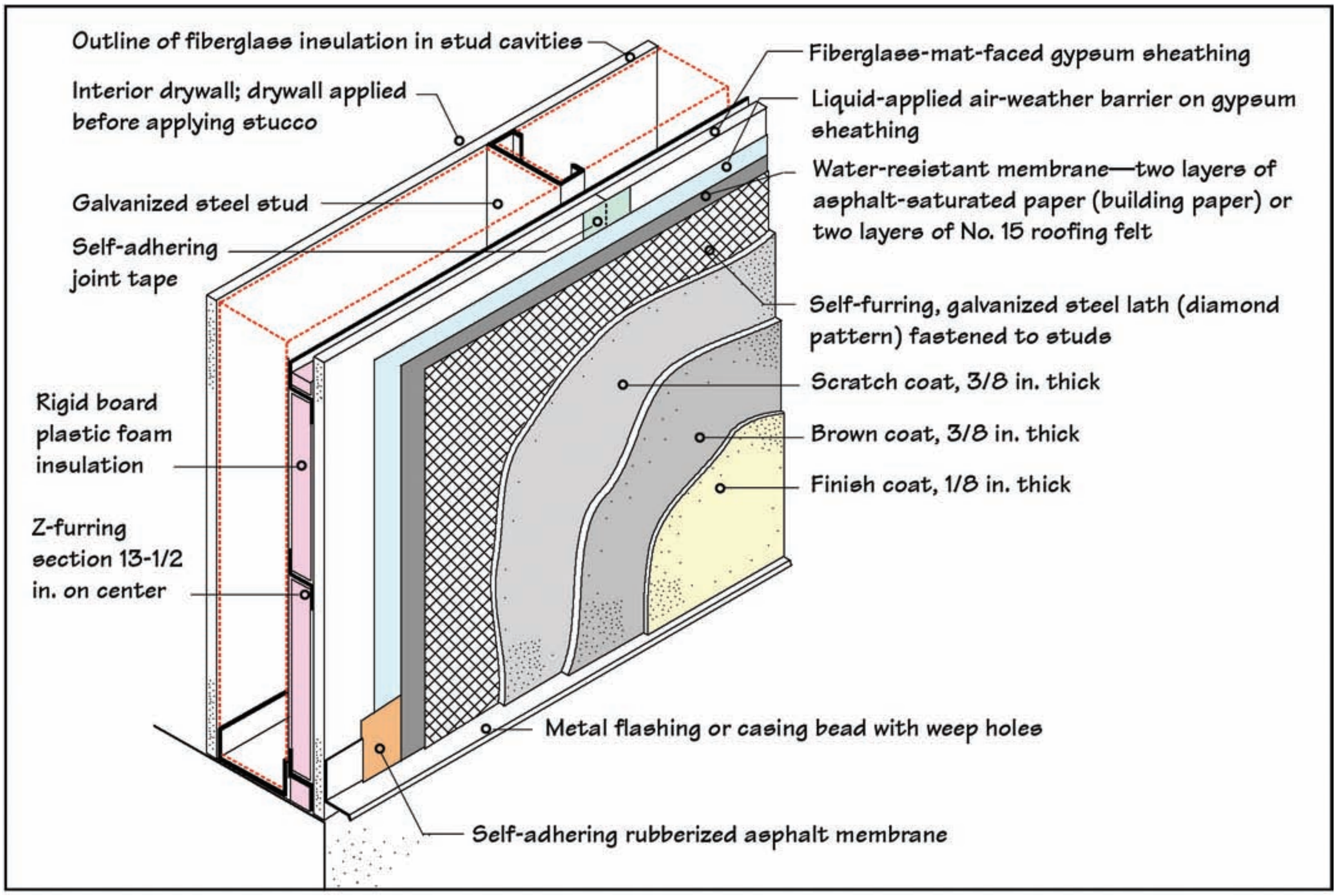

Outline of fiberglass insulation in stud cavities
Interior drywall; drywall applied before applying stucco
Galvanized steel stud
Self-adhering joint tape
Rigid board plastic foam insulation
Z-furring section 13-1/2 in. on center
Fiberglass-mat-faced gypsum sheathing
Liquid-applied air-weather barrier on gypsum sheathing
Water-resistant membrane—two layers of asphalt-saturated paper (building paper) or two layers of No. 15 roofing felt
Self-furring, galvanized steel lath (diamond pattern) fastened to studs
Scratch coat, 3/8 in. thick
Brown coat, 3/8 in. thick
Finish coat, 1/8 in. thick
Metal flashing or casing bead with weep holes
Self-adhering rubberized asphalt membrane

FIGURE 29.14 Continuous insulation and Portland cement stucco cladding. Note that Z-furring sections are spaced 13 $\frac{1}{2}$ in. on center because the metal lath comes in 27 in. × 96 in. sheets.

A major criticism of this detail is that Z-sections that support the sheathing and stucco finish are fastened to studs at a spacing of 216 sq in. (13.5 in. × 16 in. = 216 sq in.) if the studs are spaced 16 in. on center. If the studs are spaced 12 in. on center, the spacing is reduced to 162 sq in. Both these spacing are much greater than that used in a conventional stucco finish without continuous insulation, 96 sq in. for studs spaced 16 in. on center. Therefore, the detail of Figure 29.14 must be carefully engineered.

PRACTICE **QUIZ**

Each question has only one correct answer. Select the choice that best answers the question.

1. In addition to water, a stucco base coat mix consists of
  - **a.** gypsum, lime, and sand.
  - **b.** gypsum, Portland cement, and sand.
  - **c.** Portland cement, lime, and sand.
  - **d.** lime, glass fibers, and sand.

2. On wood-stud and cold-formed steel-stud-wall assemblies, stucco is typically applied in three coats. Beginning from the first to the last, the coats are generally called
  - **a.** brown coat, scratch coat, and finish coat.
  - **b.** scratch coat, brown coat, and finish coat.
  - **c.** prime coat, scratch coat, and finish coat.
  - **d.** prime coat, brown coat, and finish coat.
  - **e.** prime coat, base coat, and finish coat.

3. On wood-stud and cold-formed steel-stud-wall assemblies, stucco is typically applied in three coats. The total typical thickness of the three coats is
  - **a.** $1\frac{1}{2}$ in.
  - **b.** $1\frac{1}{4}$ in.
  - **c.** $1\frac{1}{8}$ in.
  - **d.** 1 in.
  - **e.** $\frac{7}{8}$ in.

4. The required color of a stucco surface is
  - **a.** obtained by spray painting the surface with the required color after the finish coat has fully cured.
  - **b.** obtained by spray painting the surface with the required color immediately following application of the finish coat.
  - **c.** obtained by using colored Portland cement and lime.
  - **d.** integral to the mix of all coats used in stucco.
  - **e.** integral to the mix of the finish coat.

5. Metal lath is required when stucco is applied on
  - **a.** stud-wall assemblies.
  - **b.** concrete walls.
  - **c.** masonry walls.
  - **d.** all of the above.
  - **e.** none of the above.

6. Metal lath, when used in stucco, is installed on the wall
  - **a.** before the application of the first stucco coat.
  - **b.** sandwiched between the first and second stucco coats.
  - **c.** directly under the finish coat.
  - **d.** between the second and finished stucco coats.

7. Control joints on a stucco surface are provided primarily to
  - **a.** control thermal expansion and contraction of the metal lath.
  - **b.** control thermal expansion and contraction of the stucco surface.

(*Continued*)

PRACTICE **QUIZ** *(Continued)*

c. control differential movement between the stucco surface and the substrate.
d. control drying shrinkage of stucco.

8. Control joints on a stucco surface are formed by using accessories, which consist of
a. galvanized steel. **b.** zinc.
c. PVC. **d.** any one of the above.
e. none of the above.

9. Control joints are required to be more closely spaced on a stucco surface backed by a stud wall than on a stucco surface backed by a masonry wall.
a. True **b.** False

10. The total thickness of stucco on a concrete or concrete masonry wall is generally
a. the same as that on a stud-backed wall.
b. greater than that on a stud-backed wall.
c. smaller than that on a stud-backed wall.

11. When control joints are provided in a stucco-clad wall, expansion joints are unnecessary.
a. True **b.** False

29.5 ADHERED MASONRY VENEER

As mentioned in the introduction to Chapter 28, masonry veneer may also be adhered to the backup wall in place of being anchored to it. In an adhered masonry veneer, the masonry units are relatively thin. The most commonly used adhered masonry veneer units consist of artificial (manufactured) stone with an average thickness of about $1\frac{1}{2}$ in., although natural stone and thin brick units are also used. Thin brick units range from $\frac{1}{2}$ in. to $\frac{3}{4}$ in. thick.

Apart from its lower cost, a major advantage of manufactured stone veneer is that it is light weight, 10 psf to 12 psf, compared with anchored brick veneer, which is about 30 psf. Because of its light weight, manufactured stone veneer units adhere to the backup immediately. Additionally, the units are of consistent quality and are available in various shapes, colors, and profiles, including corner units.

VENEER ANATOMY AND THE CONSTRUCTION PROCESS

The construction process and the details of an adhered masonry veneer are similar to those of stucco. Figure 29.15 shows the anatomy of adhered masonry veneer on a stud wall, which

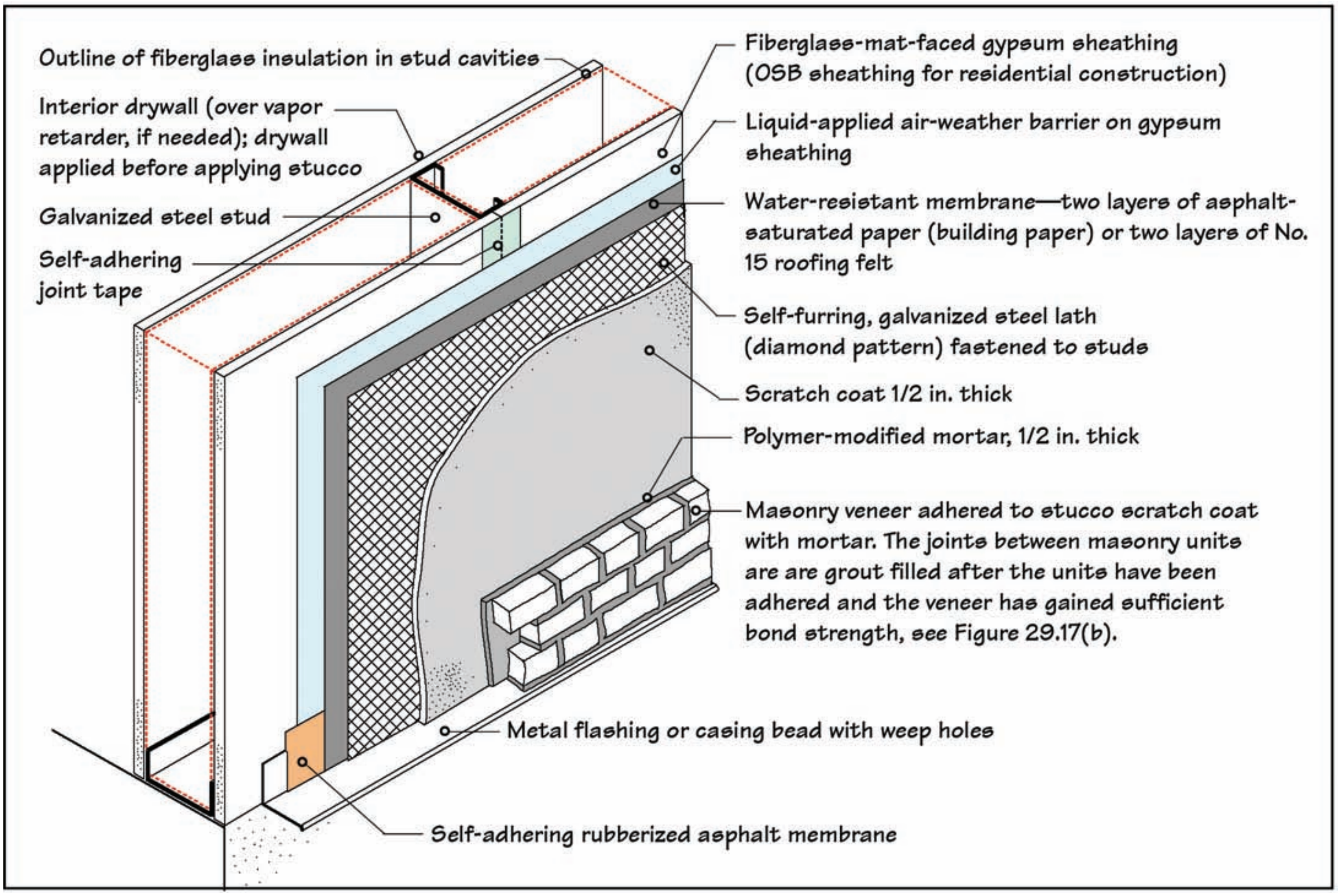
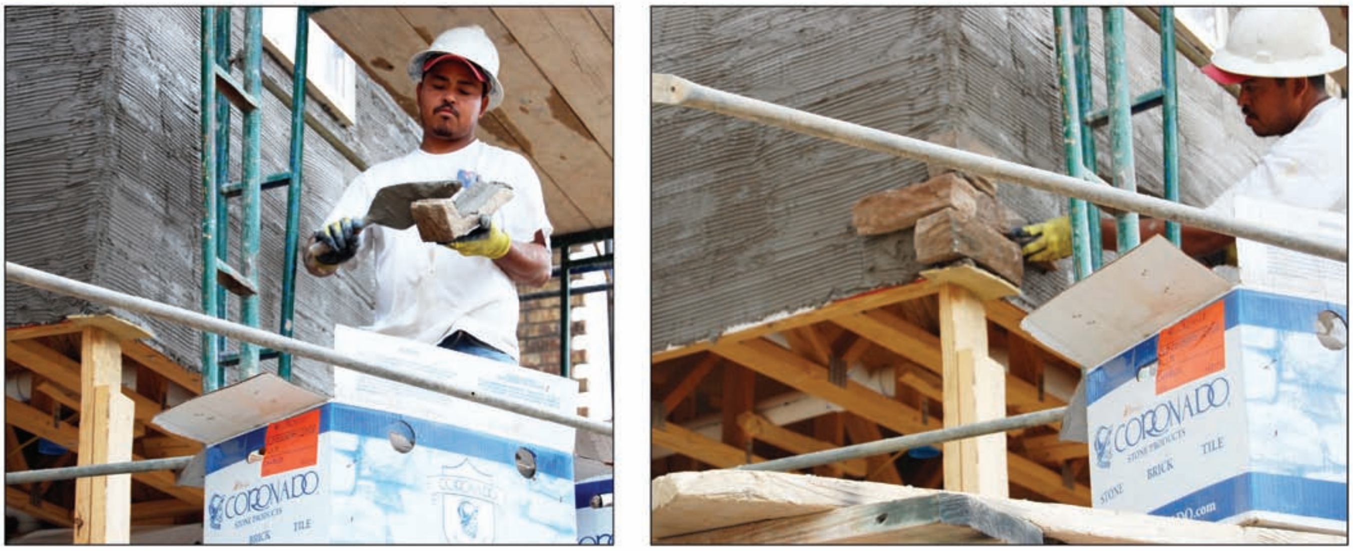

Outline of fiberglass insulation in stud cavities
Interior drywall (over vapor retarder, if needed); drywall applied before applying stucco
Galvanized steel stud
Self-adhering joint tape
Fiberglass-mat-faced gypsum sheathing (OSB sheathing for residential construction)
Liquid-applied air-weather barrier on gypsum sheathing
Water-resistant membrane—two layers of asphalt-saturated paper (building paper) or two layers of No. 15 roofing felt
Self-furring, galvanized steel lath (diamond pattern) fastened to studs
Scratch coat 1/2 in. thick
Polymer-modified mortar, 1/2 in. thick
Masonry veneer adhered to stucco scratch coat with mortar. The joints between masonry units are are grout filled after the units have been adhered and the veneer has gained sufficient bond strength, see Figure 29.17(b).
Metal flashing or casing bead with weep holes
Self-adhering rubberized asphalt membrane

FIGURE 29.15 Anatomy of an adhered masonry veneer on a (steel- or wood-) stud wall. The masonry units are generally (manufactured) lightweight stone units, $1\frac{1}{2}$ in. to 2 in. thick, as shown in Figure 29.16(a). Natural stone tiles, approximately 1 in. thick are also used in place of manufactured stone, as shown in Figure 29.17(b). The weight of the veneer units is limited to a maximum of 15 psf [Ref. 29.1].

is similar to that of Figure 29.2. A $\frac{1}{2}$-in-thick scratch coat on metal furring lath is the backup used for the veneer. After approximately 24 h of completion of the scratch coat, veneer units are adhered to the scratch-coated wall using Type S or Type N masonry mortar (see Chapter 24). Generally, $\frac{3}{8}$-in.-thick mortar is adequate, but larger thickness may be needed if the units are irregular.

Although not essential, the addition of an acrylic polymer bonding agent to the mortar is recommended. The bonding agent reduces the curing time of the mortar and increases its bond strength. Thus, typically, the mason applies the mortar to the back of the unit and presses and taps the mortared unit against the backup at the desired location. The unit adheres to the backup almost instantaneously, Figure 29.16(a). Some masons call it *lick-and-stick* masonry. The joints between the units are grouted (pointed) with mortar as soon as the bond between the units and the backup is sufficiently strong, generally after 24 h. Control joints and expansion joints in adhered masonry veneer should be treated with a backer rod and a sealant in place of grout. Figure 29.16(b) shows the wall of Figure 29.16(a) in finished state. Figures 29.17(a) and (b) show the construction of adhered masonry veneer using 1-in.-thick natural stone tiles.



A mason applying mortar to the back of the manufactured stone (corner unit)

The unit being adhered to stucco scratch coat

FIGURE 29.16(a) Construction of adhered masonry veneer consisting of lightweight manufactured stone.

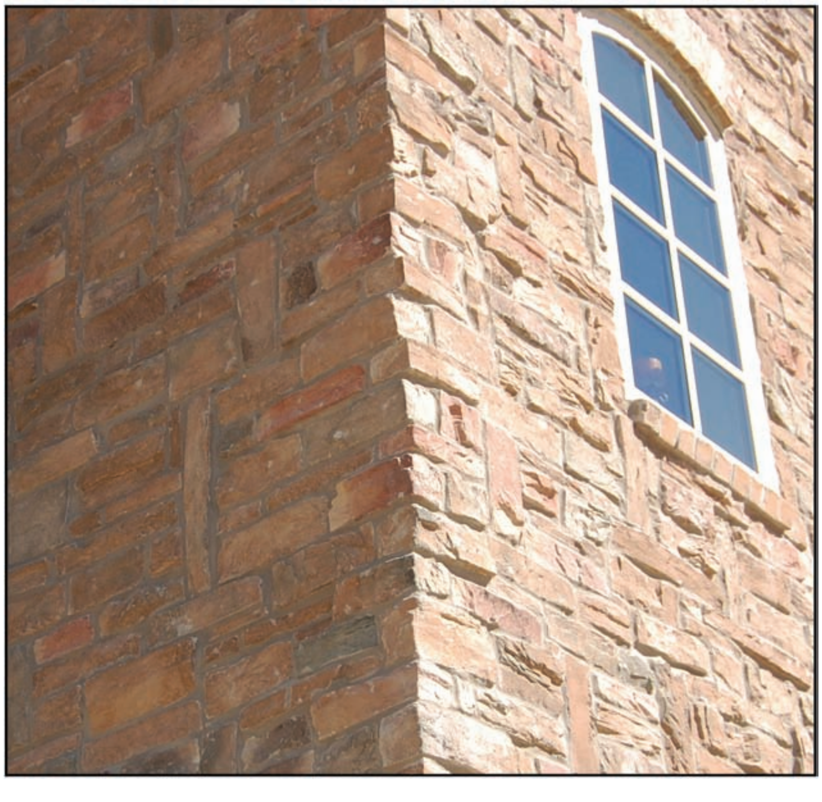


FIGURE 29.16(b) Photo of the wall with adhered masonry veneer consisting of lightweight manufactured stone on stucco scratch coat.

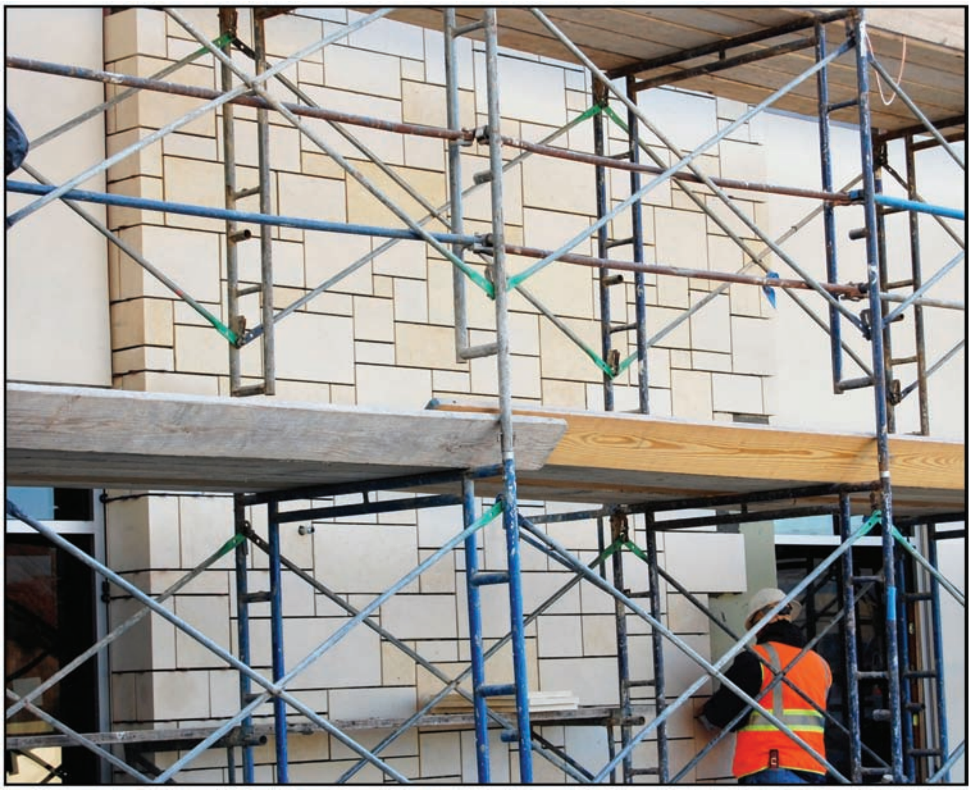
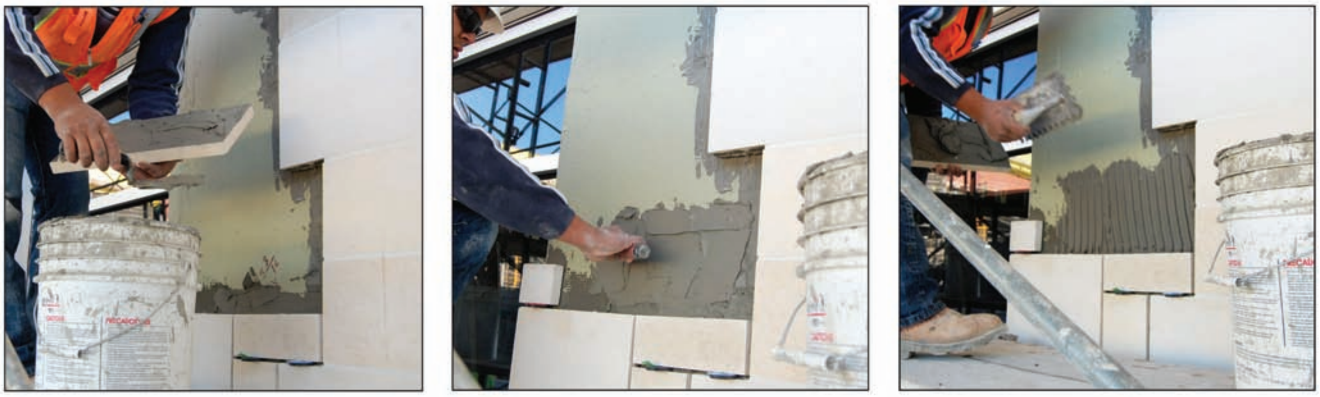


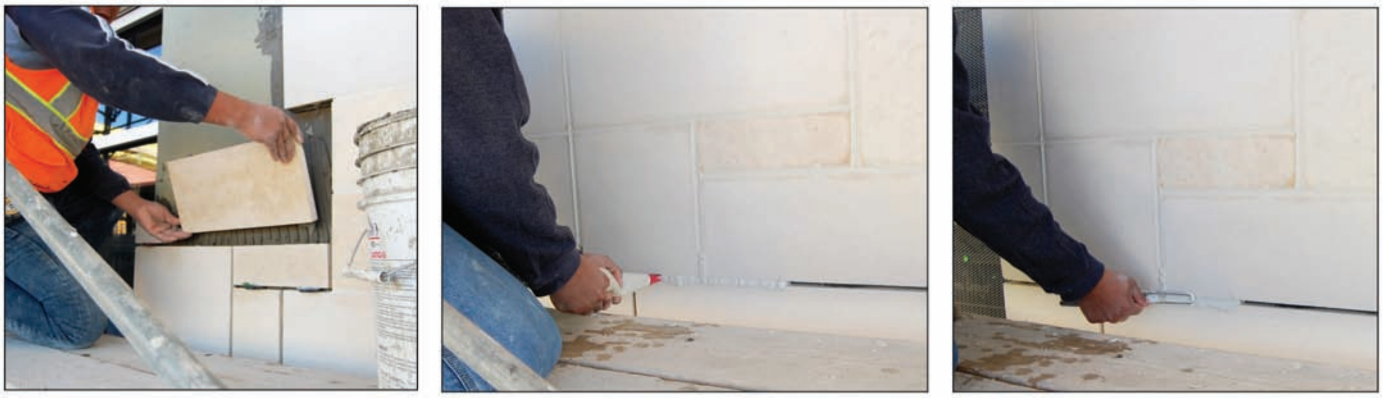
FIGURE 29.17(a) Construction of adhered veneer consisting of 1-in.-thick natural stone tiles applied on stucco scratch coat (or Portland cement board), see details in Figure 29.17(b).



Plasterer applying mortar to back of stone tile

Plasterer applying mortar to stucco scratch coat (or Portland cement board, see Figure 29.18)

Plasterer scratching the mortar applied to stucco scratch coat (or Portland cement board)



Adhering of the tile

Grouting the joint between tiles

Tooling of the grout

FIGURE 29.17(b) Details of construction of adhered veneer consisting of natural stone tiles. Note that plastic shims (not shown here) are used to obtain uniform joint width between veneer tiles.

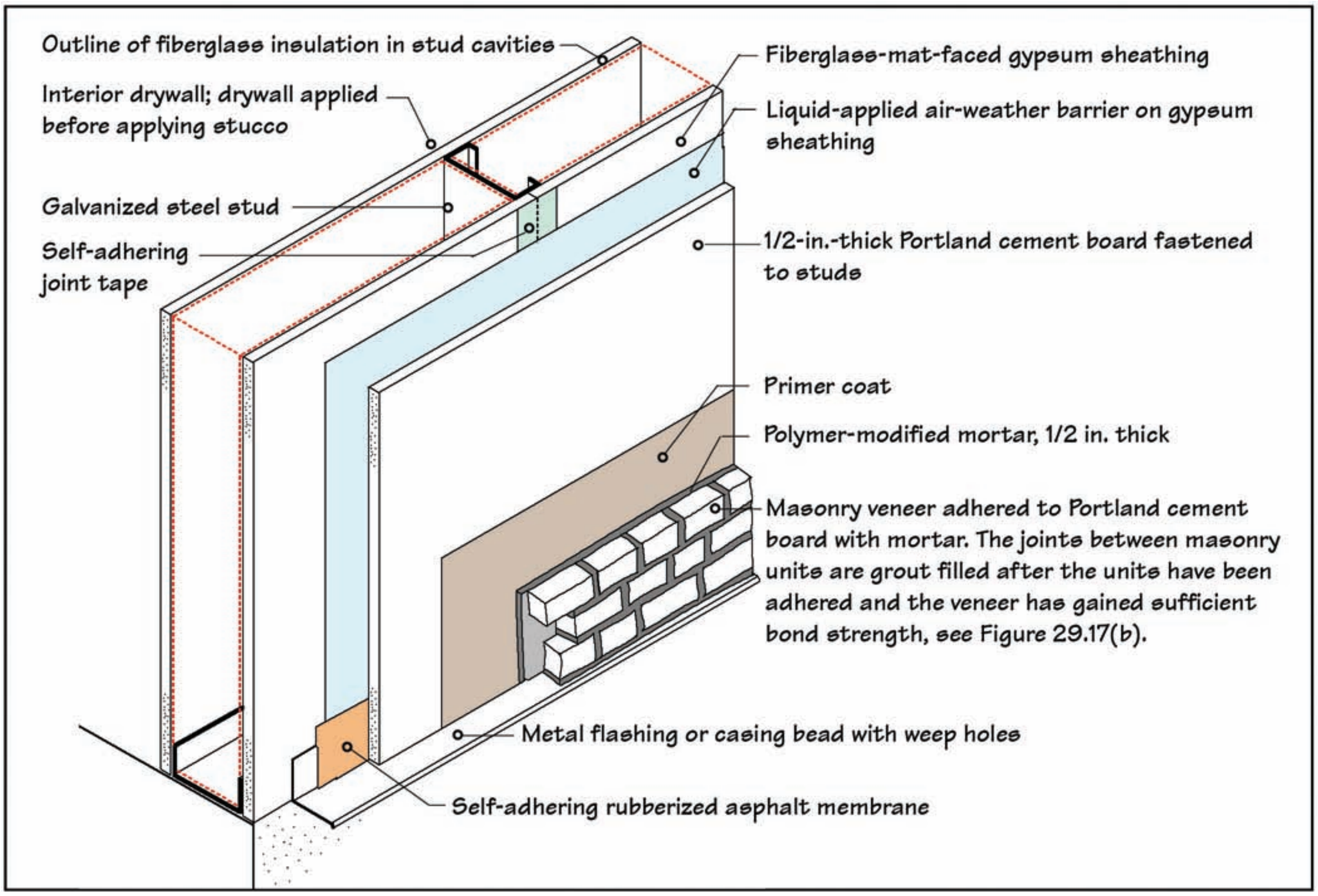

Outline of fiberglass insulation in stud cavities
Interior drywall; drywall applied before applying stucco
Galvanized steel stud
Self-adhering joint tape
Fiberglass-mat-faced gypsum sheathing
Liquid-applied air-weather barrier on gypsum sheathing
1/2-in.-thick Portland cement board fastened to studs
Primer coat
Polymer-modified mortar, 1/2 in. thick
Masonry veneer adhered to Portland cement board with mortar. The joints between masonry units are grout filled after the units have been adhered and the veneer has gained sufficient bond strength, see Figure 29.17(b).
Metal flashing or casing bead with weep holes
Self-adhering rubberized asphalt membrane

FIGURE 29.18 Anatomy of adhered masonry veneer using Portland cement board as backup in place of stucco scratch coat.

ADHERED MASONRY VENEER WITH PORTLAND CEMENT BOARD BACKUP

An alternative to the detail shown in Figure 29.15 is that of Figure 29.18. In this detail, a $\frac{1}{2}$-in.-thick Portland cement board, applied over exterior sheathing and an air-weather retarder, replaces metal furring lath and the scratch coat. Other details are essentially identical to those previously given. Because the cement board surface is not as rough as the scratch coat, manufacturers of this system have developed a surface primer that is applied over the cement board to improve the adhesion between the mortar and the board, which also improves the water resistance of the system.

29.6 EXTERIOR INSULATION AND FINISH SYSTEM (EIFS) BASICS

The exterior insulation and finish system (abbreviated EIFS and generally pronounced as "eefs") consists of a layer of a rigid polystyrene foam insulation, a fiberglass-reinforcing mesh, a polymer-based base coat, and a polymer-based finish coat. The reinforcing mesh is embedded in the base coat.

Because, in its finished appearance, an EIFS-clad facade looks like a stucco facade, it is also referred to as *synthetic stucco* to distinguish it from Portland cement stucco—the *conventional stucco*.

The description of the EIFS just given is that of a basic system. More sophisticated (and, hence, more complex) systems are available (see Section 29.8). The important fact to recognize is that an EIFS assembly is a system because it comprises several chemically complex materials. Compatibility between system parts and also among the substrate, trims and joint accessories, flashings, sealants, and so on, must be ensured. Therefore, all materials for the assembly must be obtained from one manufacturer and applied per the manufacturer's instructions. The manufacturer's warranty for the system is generally contingent on the use of its approved material distributor, certified applicator, and recommended construction details.

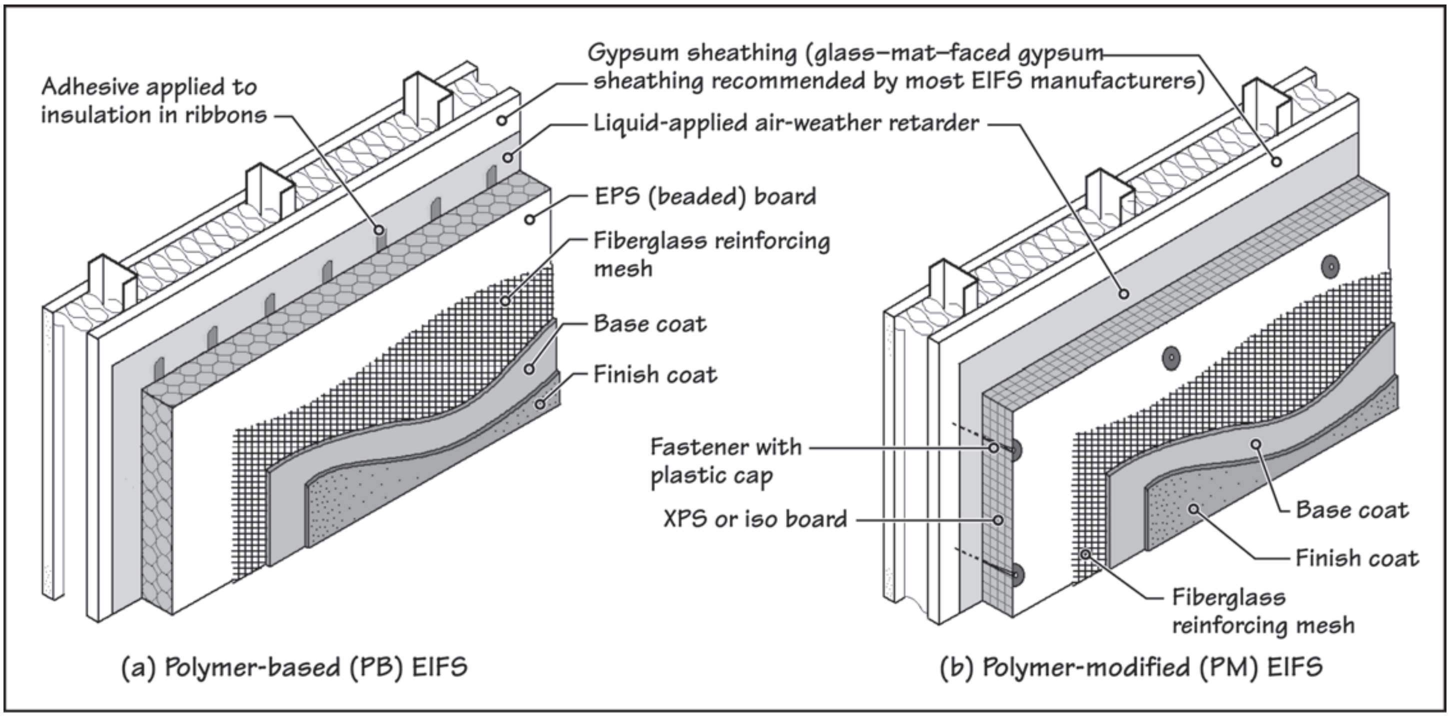

Adhesive applied to insulation in ribbons
Gypsum sheathing (glass-mat-faced gypsum sheathing recommended by most EIFS manufacturers)
Liquid-applied air-weather retarder
EPS (beaded) board
Fiberglass reinforcing mesh
Base coat
Finish coat
Fastener with plastic cap
XPS or iso board
Base coat
Finish coat
Fiberglass reinforcing mesh
(a) Polymer-based (PB) EIFS
(b) Polymer-modified (PM) EIFS

FIGURE 29.19 Difference between PB and PM EIFS.

The EIFS Industry Members Association (EIMA), a trade organization representing EIFS manufacturers, classifies an EIFS into two categories:

- Polymer-based (PB) EIFS, also called *soft-coat* EIFS
- Polymer-modified (PM) EIFS, also called *hard-coat* EIFS

In the PB system, the insulation consists of expanded polystyrene (EPS, i.e., molded and beaded) boards, which are adhered to the substrate, Figure 29.19. The total thickness of the PB EIFS lamina (mesh, base coat, and finish coat) is approximately $\frac{1}{8}$ in.

The PM system uses extruded polystyrene (XPS) or polyisocyanurate (iso) boards, which are anchored to the substrate using steel screws and plastic caps. The base coat on a PM system consists of a polymer-modified Portland cement and is at least $\frac{1}{4}$ in. thick.

The PB system is far more commonly used and is the one described here in further detail. Although most manufacturers' systems are similar, there are differences between them. Therefore, the manufacturer's literature should be consulted for more authoritative information.

29.7 APPLICATION OF POLYMER-BASED EIFS

EIFS is a versatile cladding and is used for all types of projects—low-rise, mid-rise, and high-rise buildings—in commercial as well as residential projects. It can be used over wood frame, cold-formed steel-stud frame, concrete, or masonry walls.

The use of rigid foam insulation in EIFS has several advantages. First, it is energy efficient because placing insulation on the exterior of a wall assembly results in a higher effective R-value than placing it within or toward the interior of the assembly (see Section 5.9).

Second, the foam insulation allows a great deal of detail work to be easily incorporated on the facade. The foam can be molded to shape, it can be cut out to provide grooves for surface relief, and its thickness can be varied to give accent bands. The surface detail remains virtually unchanged after the application of the base and finish coats because of their relatively small total thickness.

Third, a large variety of colors are available in an EIFS finish coat. Most EIFS-clad facades are richly detailed and variously colored. Few other cladding materials lend themselves to such ornateness and bright, relatively fade-resistant colors as EIFS. Therefore, a mock-up panel of EIFS cladding is all the more important in most projects, Figure 29.20.

Fourth, EIFS does not require control joints, such as those used with stucco, adding to its versatility. Fifth, EIFS is one of the least expensive exterior wall claddings available today—less than any other system discussed in this and the previous chapter.

EIFS is, however, not without problems. Its low impact resistance and its inability to breathe (in contrast with Portland cement stucco) create problems (see Section 29.8).

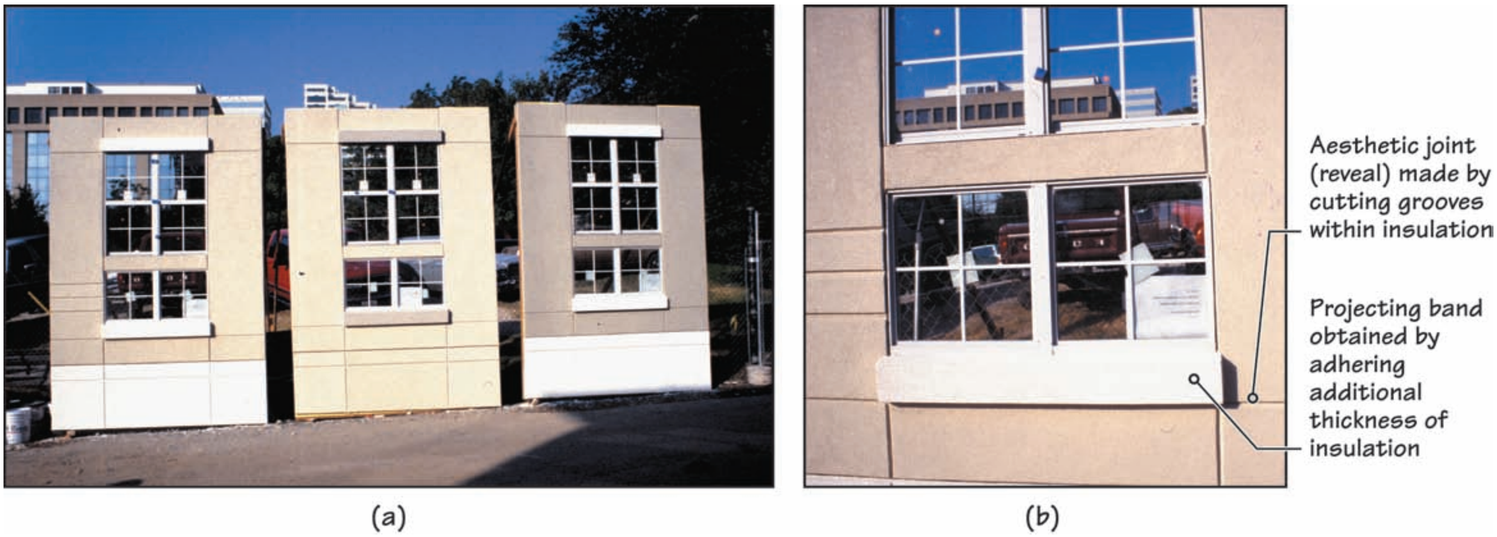

Aesthetic joint (reveal) made by cutting grooves within insulation
Projecting band obtained by adhering additional thickness of insulation
(a)
(b)

FIGURE 29.20 **(a)** To make a selection, three facade alternatives (mock-ups) were requested by the architect from the EIFS subcontractor for use in a high-rise condominium. **(b)** A close-up of one of the mock-ups shown in Figure 29.20(a).

INSTALLATION OF INSULATION

The first step in the application of PB EIFS is to adhere the insulation over the liquid-applied air-weather retarder placed over the substrate. The adhesive is applied to the back of the insulation in ribbons using a notched trowel, Figure 29.21. (Alternatively, adhesive daubs and perimeter strips may be used, Figure 29.22(a).) After the adhesive is applied, the board is pressed against the substrate, to which it clings instantaneously because of its light weight. The boards are arranged in a running-bond pattern to avoid continuous joints, Figure 29.22(b).

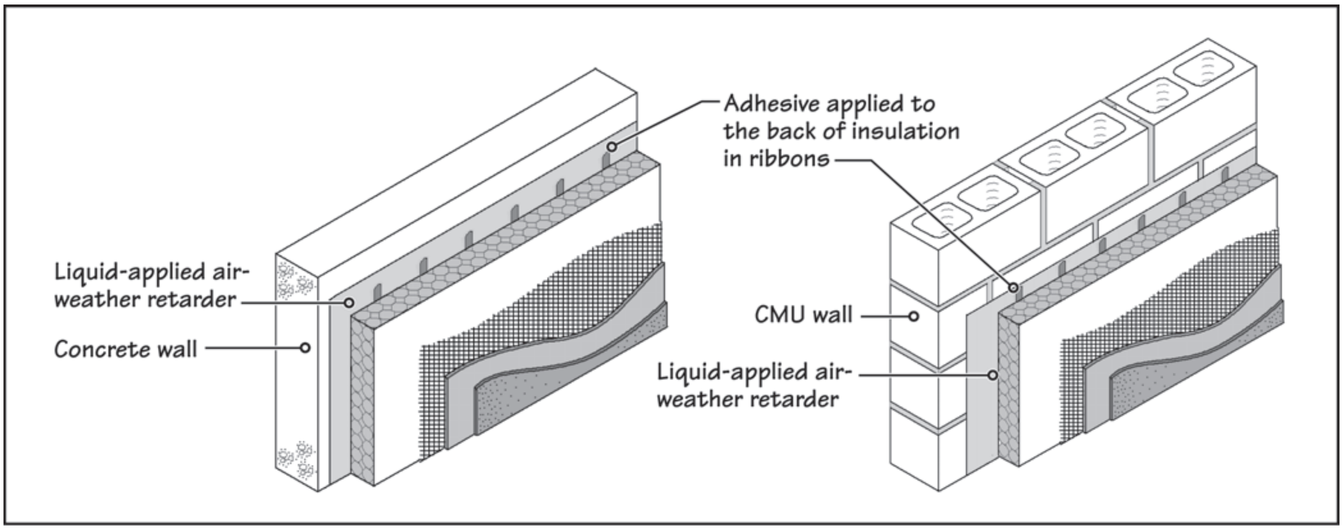

Adhesive applied to the back of insulation in ribbons
Liquid-applied air-weather retarder
Concrete wall
CMU wall
Liquid-applied air-weather retarder

FIGURE 29.21 EIFS on a concrete or CMU wall. Manufacturer-provided adhesive is applied to the back of an insulation board, which is then pressed against the concrete or CMU wall.

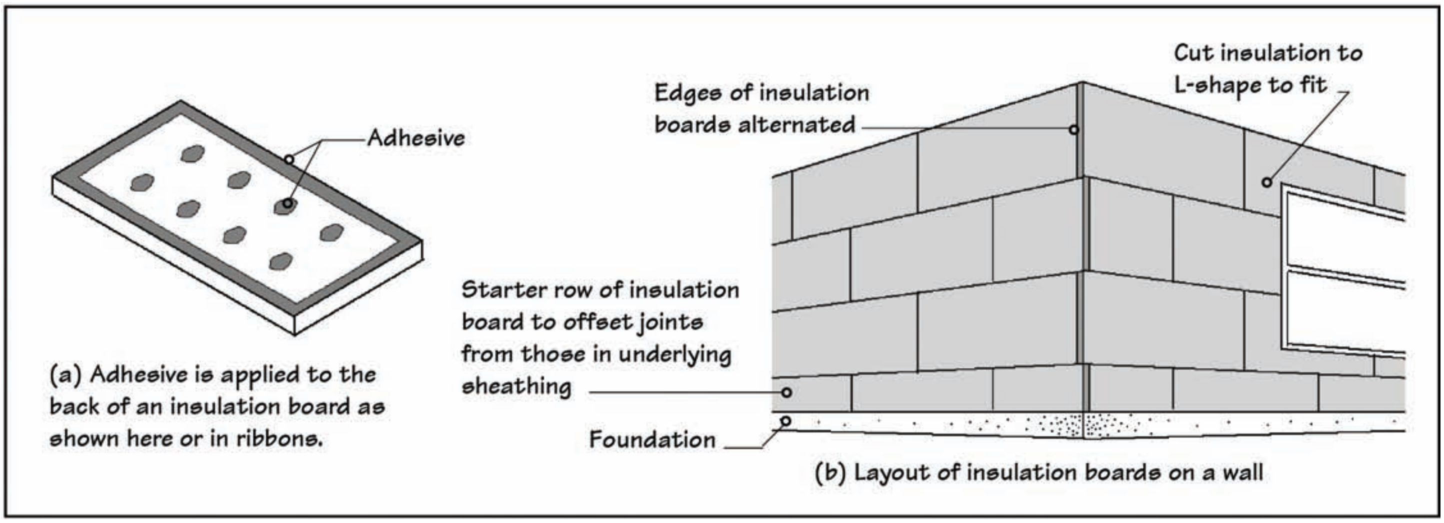

Adhesive
(a) Adhesive is applied to the back of an insulation board as shown here or in ribbons.
Edges of insulation boards alternated
Cut insulation to L-shape to fit
Starter row of insulation board to offset joints from those in underlying sheathing
Foundation
(b) Layout of insulation boards on a wall

FIGURE 29.22 **(a)** An alternative method of applying adhesive to the back of an insulation board using daubs of adhesive (instead of ribbons of adhesive). **(b)** Layout of insulation boards on a wall.

Once the insulation boards have been installed, they are sanded smooth, a process known as *rasping*. Rasping removes surface irregularities resulting from an uneven substrate or uneven insulation boards, Figure 29.23. Generally, more than one sander grade is needed to obtain the required surface. If aesthetic grooves are needed, they are cut into the insulation boards at this stage, Figure 29.24. The minimum thickness of insulation behind the groove must at least be $\frac{3}{4}$ in.

APPLICATION OF THE EIFS LAMINA (BASE COAT, MESH, AND FINISH COAT)

Before the base coat is applied, the terminal edges of insulation boards—at the foundation and around openings—are wrapped with *reinforcing mesh*, a process known as *backwrapping*, Figure 29.25. The reinforcing mesh is embedded in the base coat. Backwrapping strengthens the edges and functions like casing bead in conventional stucco.

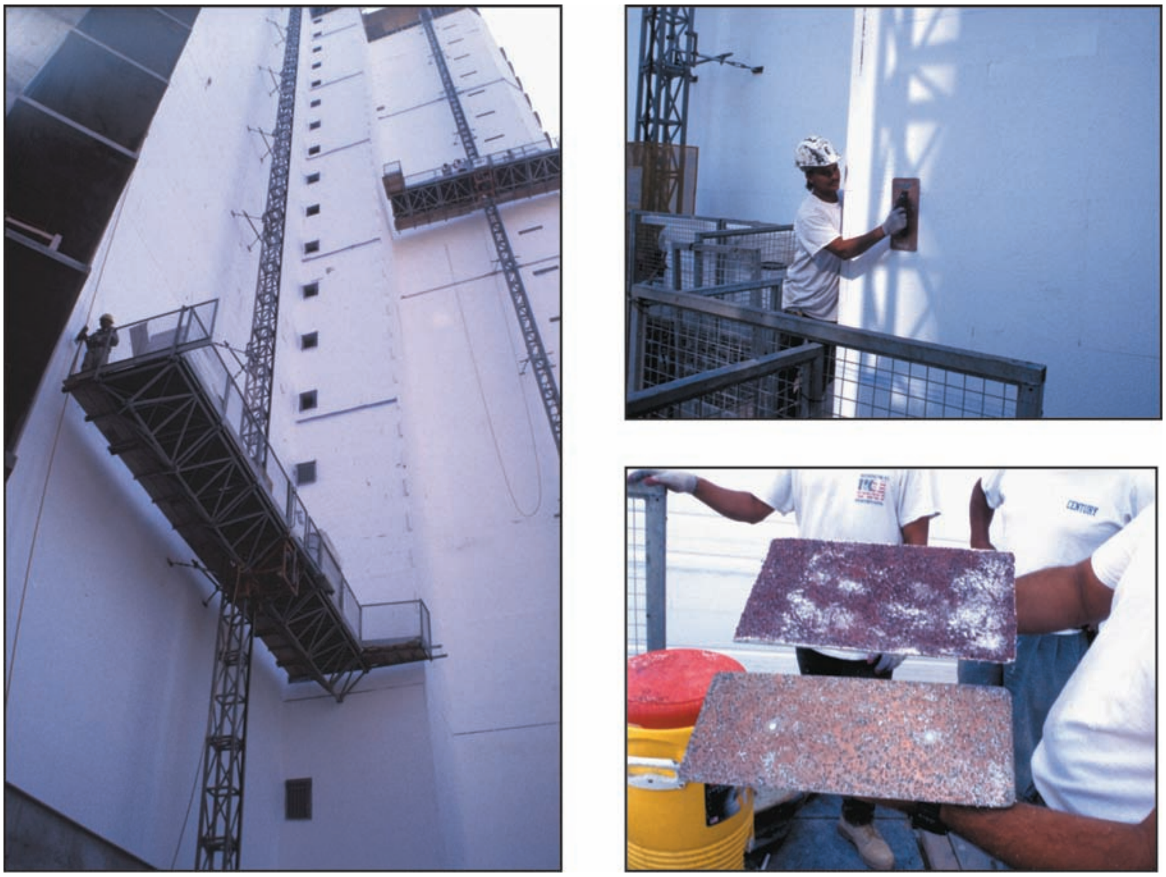
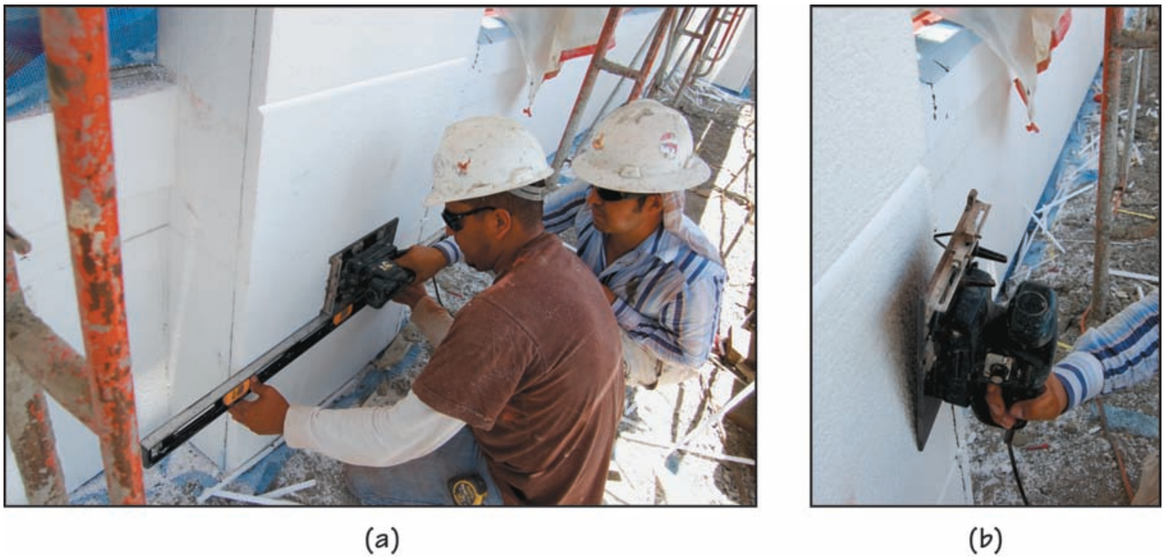


FIGURE 29.23 After the insulation has been adhered to the substrate, it is sanded smooth, a process called *rasping*. The right-hand lower photo shows two rasps with different roughness grades.



(a) (b)

FIGURE 29.24 **(a)** Cutting of reveals (aesthetic grooves) in the insulation after it has been adhered to the substrate with the help of a groove-making tool and a level. **(b)** A close-up of the groove-making tool that makes a V-shaped groove. The tool can be adapted to make grooves with different profiles.

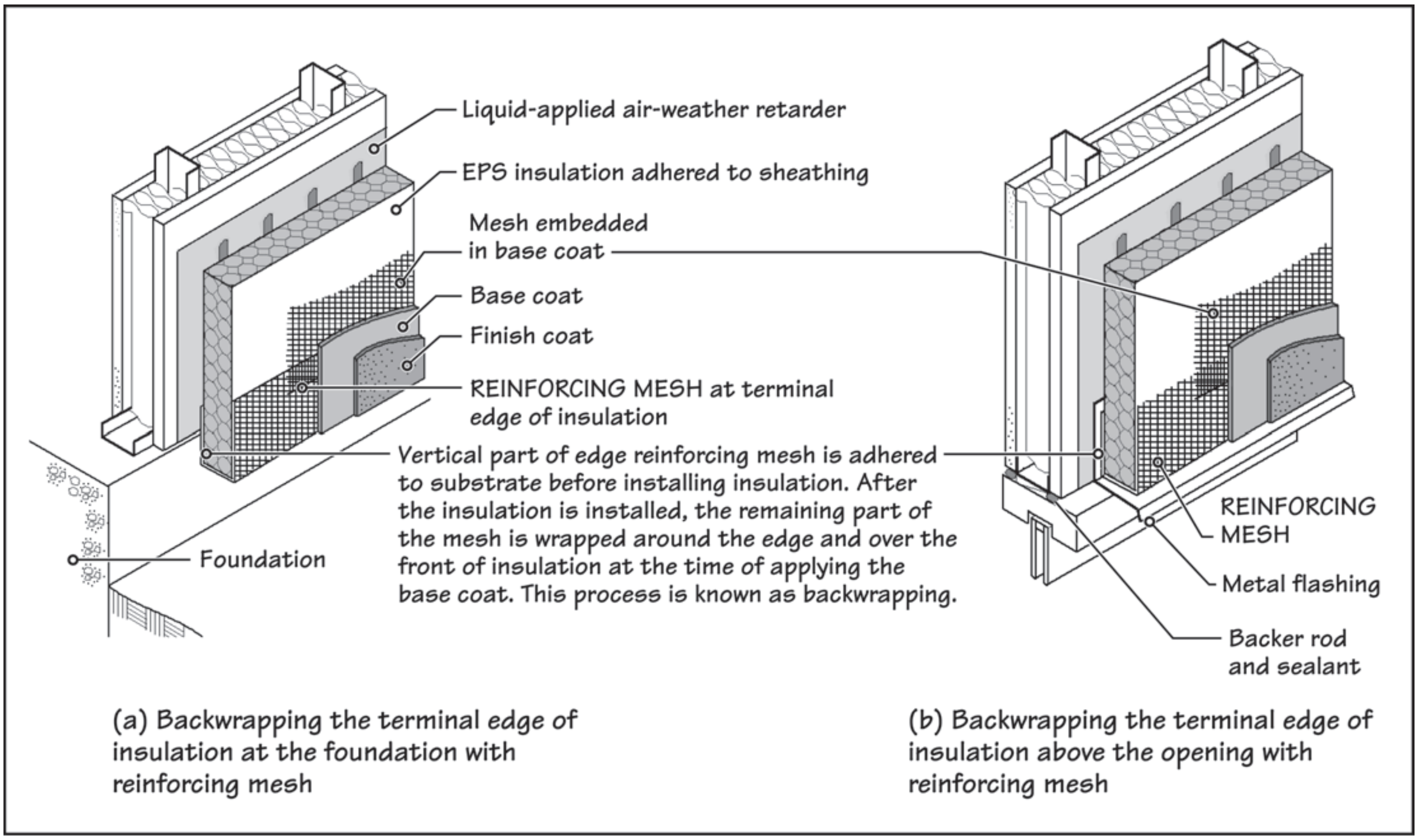

Liquid-applied air-weather retarder
EPS insulation adhered to sheathing
Mesh embedded in base coat
Base coat
Finish coat
REINFORCING MESH at terminal edge of insulation
Vertical part of edge reinforcing mesh is adhered to substrate before installing insulation. After the insulation is installed, the remaining part of the mesh is wrapped around the edge and over the front of insulation at the time of applying the base coat. This process is known as backwrapping.
Foundation
REINFORCING MESH
Metal flashing
Backer rod and sealant
(a) Backwrapping the terminal edge of insulation at the foundation with reinforcing mesh
(b) Backwrapping the terminal edge of insulation above the opening with reinforcing mesh

FIGURE 29.25 Backwrapping of insulation, that is, wrapping the terminal edges of insulation with reinforcing mesh.

After the edges are wrapped, the base coat is applied. Immediately afterward, the mesh is unrolled over the base coat and, using the trowel and some additional base coat material, the mesh is fully embedded in the base coat, Figure 29.26. The finish coat is either sprayed or troweled on the base coat.

MOVEMENT CONTROL IN AN EIFS WALL

Because both the base coat and the finish coat are polymer based, the EIFS lamina is a relatively flexible membrane. Therefore, an EIFS-clad wall does not require any control joints. Expansion joints are, however, required where large movements in the structure or substrate are expected. These locations are (a) at the spandrel beam level, (b) where an EIFS-clad wall abuts a wall of a different material, (c) at a major change in wall elevation, and (d) at a building expansion joint. Figure 29.27 shows a typical expansion joint detail in an EIFS wall.

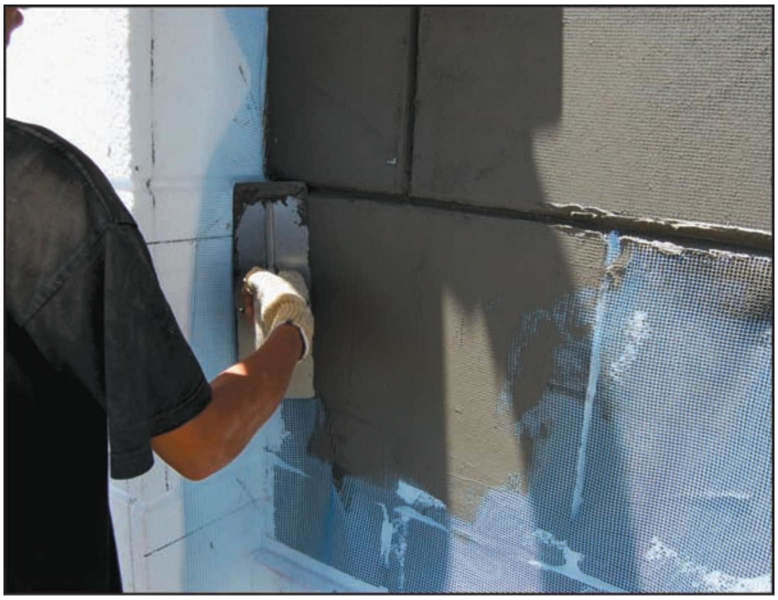


FIGURE 29.26 In applying the base coat, the base coat adhesive is first troweled on the insulation. Then the mesh is unrolled over the adhesive and an additional layer of base coat adhesive is applied. This embeds the mesh fully in the base coat.

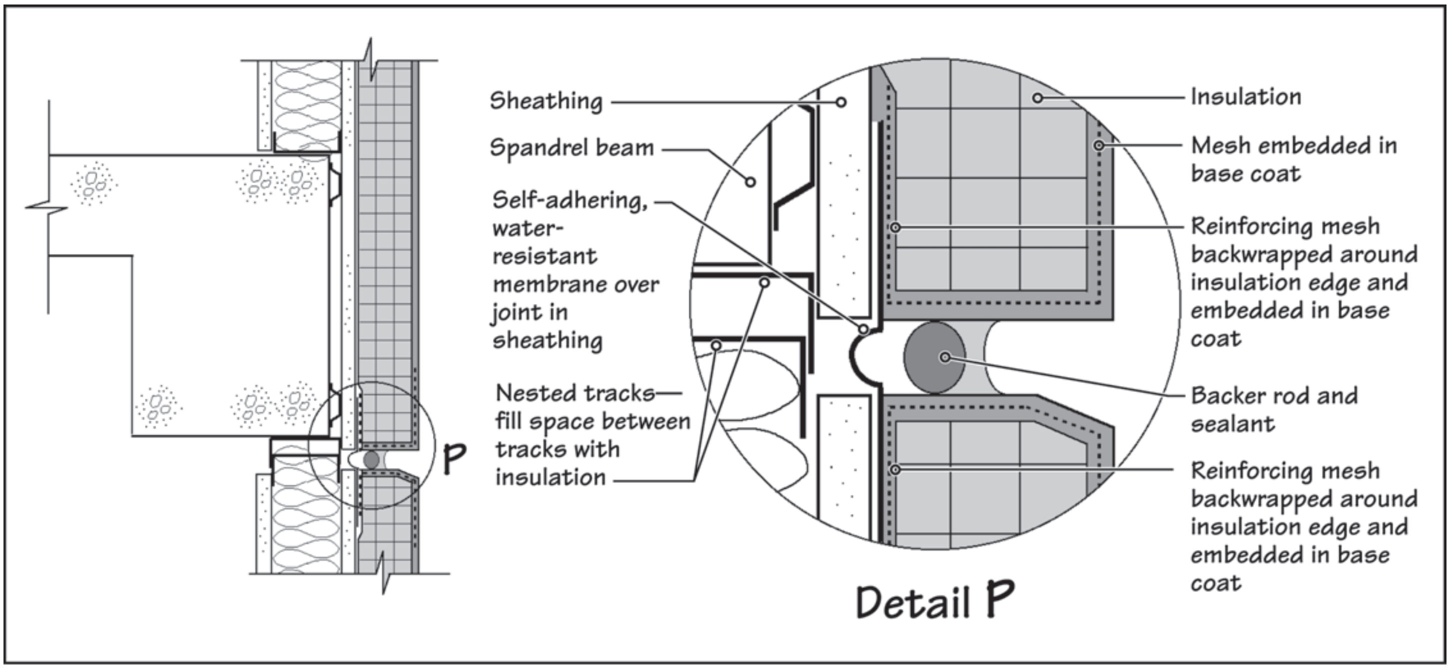

Sheathing
Spandrel beam
Self-adhering, water-resistant membrane over joint in sheathing
Nested tracks— fill space between tracks with insulation
P
Insulation
Mesh embedded in base coat
Reinforcing mesh backwrapped around insulation edge and embedded in base coat
Backer rod and sealant
Reinforcing mesh backwrapped around insulation edge and embedded in base coat
Detail P

FIGURE 29.27 A typical expansion joint detail in an EIFS-clad wall.

29.8 IMPACT-RESISTANT AND DRAINABLE EIFS

As stated earlier, there are two major concerns in the standard EIFS cladding system described in the previous section. The first concern is its low resistance to impact. This is due to the low compressive strength of EPS insulation and the thinness of the EIFS lamina. Damage by hailstorms has been reported on EIFS cladding, particularly on horizontal surfaces, such as aesthetic bands and window sills.

The second concern is that an EIFS-clad wall is a barrier wall. Being polymer based, it does not breathe as well as a Portland cement stucco wall. Any water that permeates through an EIFS cladding will generally take a long time to evaporate. This leads to an overall deterioration of the wall assembly and may result in the growth of mold in some walls. Therefore, good workmanship and quality control during application and good detailing with respect to flashing and sealants, particularly around openings and terminations, are extremely important in an EIFS-clad wall. To address these concerns, EIFS manufacturers have introduced an impact-resistant EIFS and a drainable EIFS.

IMPACT-RESISTANT EIFS

An impact-resistant EIFS consists of two layers of base coat. The first layer is embedded in a thicker reinforcing mesh, and the second layer has the same mesh as the standard EIFS, Figure 29.28. Although the impact-resistant EIFS has higher compressive strength than

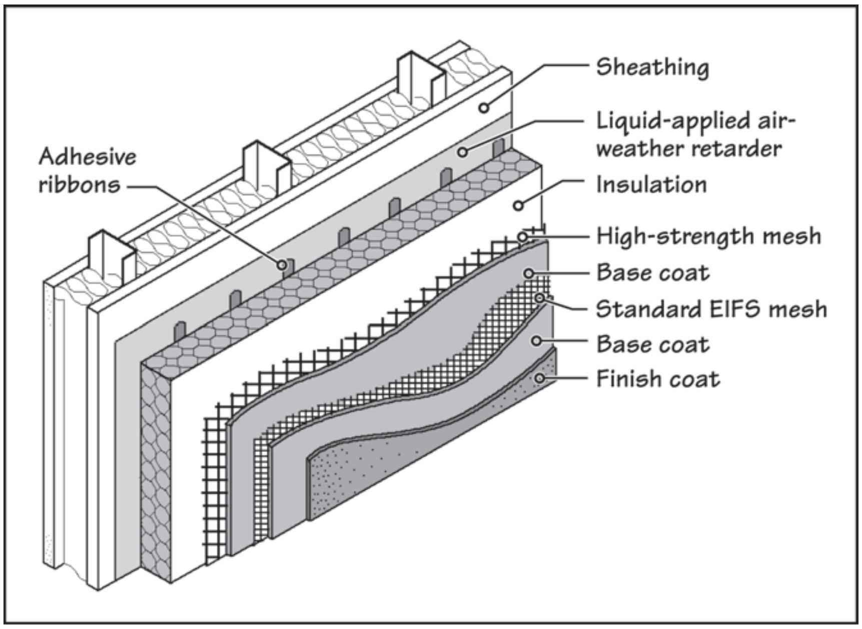

Adhesive ribbons
Sheathing
Liquid-applied air-weather retarder
Insulation
High-strength mesh
Base coat
Standard EIFS mesh
Base coat
Finish coat

FIGURE 29.28 Anatomy of an impact-resistant EIFS assembly.

the standard EIFS, it is not equivalent to the compressive strength of most other cladding systems. Therefore, in many projects, the first few floors of the building are clad with a high-compressive-strength cladding, such as masonry veneer, concrete, or stucco, and the higher floors are clad with EIFS.

DRAINABLE EIFS

Two types of drainable EIFS wall systems are available. The system with insulation adhered to the substrate has vertical drainage grooves at the back of the insulation, Figure 29.29.

The other system, in which the insulation is mechanically anchored to the substrate, has a thin drainage mat and an air-weather retarder behind the insulation, Figure 29.30. The drainage mat is typically made of interwoven plastic strands. As an alternative to the mat and building paper, one manufacturer uses a layer of synthetic material with drainage lines.

Both systems require a perforated plastic track at the bottom to allow water to weep at the base. (The bottom track is similar to a casing bead in a Portland cement stucco wall.) In a multistory building, the tracks are provided at each floor level.

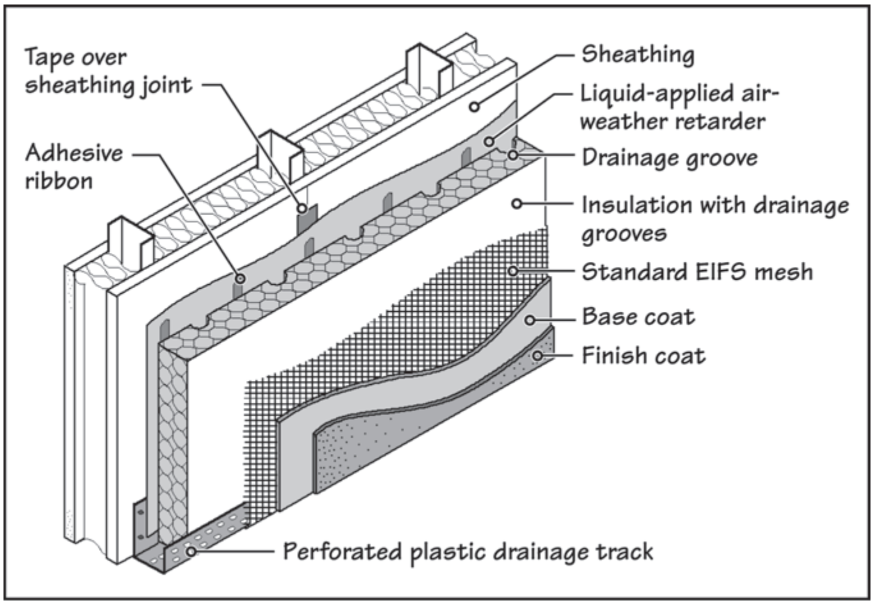

Tape over sheathing joint
Adhesive ribbon
Sheathing
Liquid-applied air-weather retarder
Drainage groove
Insulation with drainage grooves
Standard EIFS mesh
Base coat
Finish coat
Perforated plastic drainage track

FIGURE 29.29 Drainable EIFS system in which the insulation is adhered to the substrate and the drainage is provided by vertical grooves in the insulation.

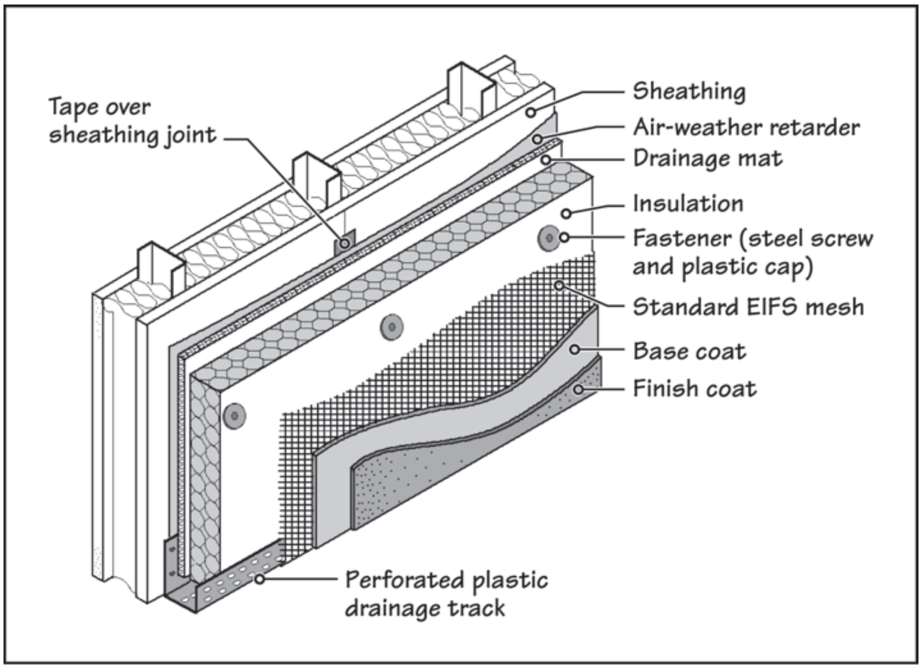

Tape over sheathing joint
Sheathing
Air-weather retarder
Drainage mat
Insulation
Fastener (steel screw and plastic cap)
Standard EIFS mesh
Base coat
Finish coat
Perforated plastic drainage track

FIGURE 29.30 Drainable EIFS system in which the insulation is mechanically fastened to the wall framing members and the drainage is provided by a drainage mat made of interwoven plastic strands.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

12. In an adhered masonry veneer, the most commonly used masonry unit is
- **a.** terracotta tiles.
- **b.** regular bricks.
- **c.** concrete masonry units (CMUs).
- **d.** natural stone.
- **e.** lightweight manufactured stone.

13. In an adhered masonry veneer, masonry units are adhered to the backup surface using
- **a.** polymer-modified masonry mortar.
- **b.** epoxy resin.
- **c.** Portland cement slurry.
- **d.** an acrylic polymer bonding agent.
- **e.** any one of the above.

14. Masonry units in an adhered masonry veneer on a stud wall are applied directly on
- **a.** gypsum sheathing.
- **b.** gypsum sheathing treated with a liquid-applied air-weather retarder.
- **c.** a stucco scratch coat over metal furring lath.
- **d.** a stucco brown coat.
- **e.** any one of the above.

15. Masonry units in an adhered masonry veneer
- **a.** require pointing of joints before adhering the units.
- **b.** require grouting of joints after adhering the units.
- **c.** require grouting of joints while the units are being adhered.
- **d.** do not require pointing of joints.

16. The term *EIFS* is an acronym for
- **a.** exterior insulation and finished stucco.
- **b.** exterior insulation and finish system.
- **c.** externally insulated finish system.
- **d.** envelope insulation with finished stucco.

17. EIFS is classified into two categories: polymer-based (PB) EIFS and polymer-modified (PM) EIFS. Which of these two is more commonly used?
- **a.** PB EIFS
- **b.** PM EIFS

18. In PB EIFS, the insulation commonly used is
- **a.** fiberglass.
- **b.** polyisocyanurate.
- **c.** extruded polystyrene.
- **d.** expanded polystyrene.
- **e.** none of the above.

19. In PB EIFS, the EIFS lamina consists of
- **a.** base coat, insulation, and finish coat.
- **b.** base coat, mesh, and finish coat.
- **c.** insulation, mesh, and finish coat.
- **d.** insulation, lath, base coat, and finish coat.

20. The thickness of the lamina in PB EIFS is approximately
- **a.** 1 in.
- **b.** $\frac{1}{2}$ in.
- **c.** $\frac{1}{4}$ in.
- **d.** $\frac{1}{8}$ in.
- **e.** $\frac{1}{16}$ in.

21. Backwrapping in an EIFS-clad wall refers to
- **a.** wrapping the edges of the openings in the wall with a water-resistant tape.
- **b.** wrapping the terminal edges of EIFS insulation with EIFS mesh.
- **c.** wrapping the joints between EIFS insulation with EIFS mesh.
- **d.** wrapping the joints between EIFS insulation with a water-resistant tape.

22. The requirements for control joints in an EIFS wall are
- **a.** generally the same as those in a stucco-clad wall.
- **b.** more stringent than those in a stucco-clad wall.
- **c.** less stringent than those in a stucco-clad wall.
- **d.** none; control joints are not required in an EIFS-clad wall.

23. Impact-resistant EIFS generally has
- **a.** one base coat and one finish coat.
- **b.** one base coat and two finish coats.
- **c.** two base coats and two finish coats.
- **d.** two base coats and one finish coat.
- **e.** three base coats and one finish coat.

24. Expansion joints are required in an EIFS-clad wall.
- **a.** True
- **b.** False

29.9 EXTERIOR CLADDING WITH DIMENSION STONE

Granite, marble, and limestone are the three stones commonly used for exterior cladding. The minimum recommended thickness for exterior granite cladding slabs is $1\frac{1}{4}$ in. (3 cm) with a panel size of 20 ft^2 or less. The corresponding thickness for marble and limestone is 2 in. (5 cm). Greater thickness is used for larger slab sizes or for greater durability.

Stone cladding can either be field installed, slab by slab, at the construction site or prefabricated into curtain wall panels. Field installation can be done by one of the following two methods:

- Standard-set installation
- Vertical channel support installation

NOTE

Quarter-Point Supports

Quarter-point dead-load supports for slabs (as shown in Figure 29.31) give uniform center-to-center spacing between supports and also produce the least bending stresses in slabs.

29.10 FIELD INSTALLATION OF STONE—STANDARD-SET METHOD

In the standard-set method, each stone slab is directly anchored to the backup wall with its own dead-load and lateral-load supports. Two dead-load supports are required for each slab, which are provided by stone liner blocks. The liner blocks are bolted to the slab at a stone-fabrication plant with stainless steel bent bolts set in epoxy resin (typically at quarter points), Figure 29.31.

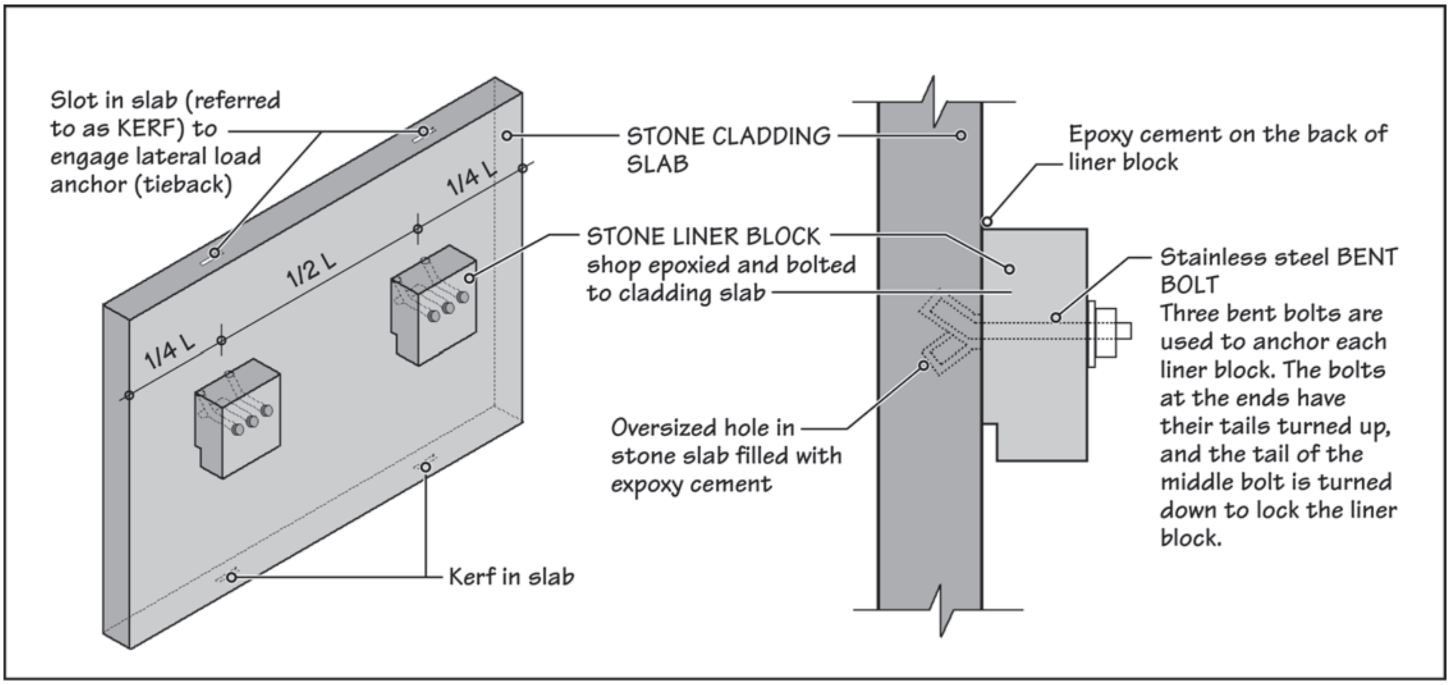

Slot in slab (referred to as KERF) to engage lateral load anchor (tieback)
1/4 L
1/2 L
1/4 L
STONE CLADDING SLAB
STONE LINER BLOCK shop epoxied and bolted to cladding slab
Oversized hole in stone slab filled with expoxy cement
Kerf in slab
Epoxy cement on the back of liner block
Stainless steel BENT BOLT
Three bent bolts are used to anchor each liner block. The bolts at the ends have their tails turned up, and the tail of the middle bolt is turned down to lock the liner block.

FIGURE 29.31 A stone cladding slab with liner blocks at quarter points.

In installing stone slabs, each liner block is made to bear on a J-shaped shelf angle clip that is anchored to a CMU or reinforced-concrete backup wall, Figures 29.32 and 29.33. A setting pad that functions as a cushion and a shim is typically used under each liner block.

Tieback anchors provide lateral-load supports and consist of split-tail anchors, whose tails engage in the slots (kerfs) provided in the cladding slabs, Figure 29.34. Split-tail anchors may be secured to the backup wall directly, as shown in Figure 29.35. Alternatively, they may be secured through a clip angle anchored to the backup wall, Figure 29.36. Securing the split-tail anchors through an angle provides greater adjustability in their location.

The kerfs in stone slabs must be filled completely with fast-curing sealant before inserting the anchors, Figure 29.37. An incomplete seal may lead to intrusion of rainwater in them, causing freeze-thaw damage to stone slabs.

The number of tieback anchors is determined by the load resistance of each anchor and the magnitude of lateral loads. However, a minimum of four anchors are required for a slab area of up to 12 ft^2, with additional anchors for a larger area, as needed.

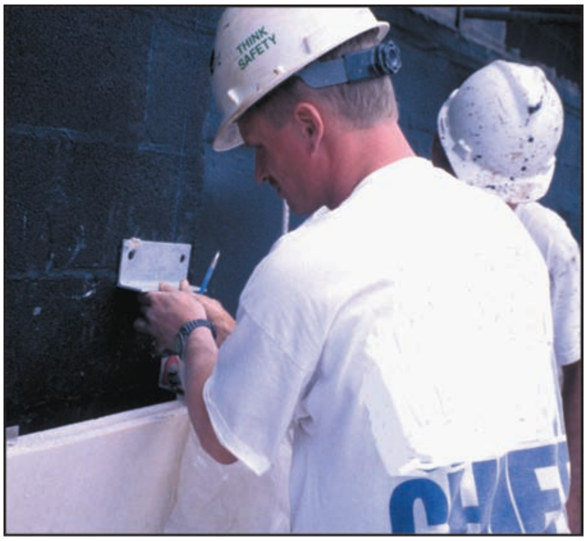

THINK SAFETY

FIGURE 29.32 Anchorage of a J-shaped shelf angle clip to a CMU backup wall whose surface has been treated with a liquid-applied air-weather retarder.

BENT-PLATE CLIPS AS AN ALTERNATIVE TO STONE LINER BLOCKS

A commonly used substitute for a stone liner block is a stainless steel bent-plate clip, referred to as a *bayonet clip*, Figure 29.38. Slabs with bayonet clips have less stone and, therefore, a smaller dead load than slabs with liner blocks. Bayonet clips (two per slab) are bolted and epoxied to the cladding slab in the same way as liner blocks.

DEAD-LOAD SUPPORT AND TIEBACK ANCHOR IN ONE CLIP ANCHOR

The dead-load supports and tieback anchors for stone slabs can be combined in one clip anchor, which is fabricated from two stainless steel members—a bent plate and a flat plate, Figure 29.39. The use of one anchor substantially facilitates the installation of cladding. At locations where flashing is required, dead-load supports and tieback clip anchors need to be separated, as shown in Detail Q of Figure 29.40.

With rigid foam insulation provided between the cladding and the CMU backup wall, the insulation must be cut around dead-load supports and tieback anchors, Figure 29.41. In such a case, the anchorage clips may be required to be heavier or braced.

The details shown previously can be modified if the backup wall consists of a cold-formed steel-stud wall instead of a CMU backup wall, Figure 29.42.

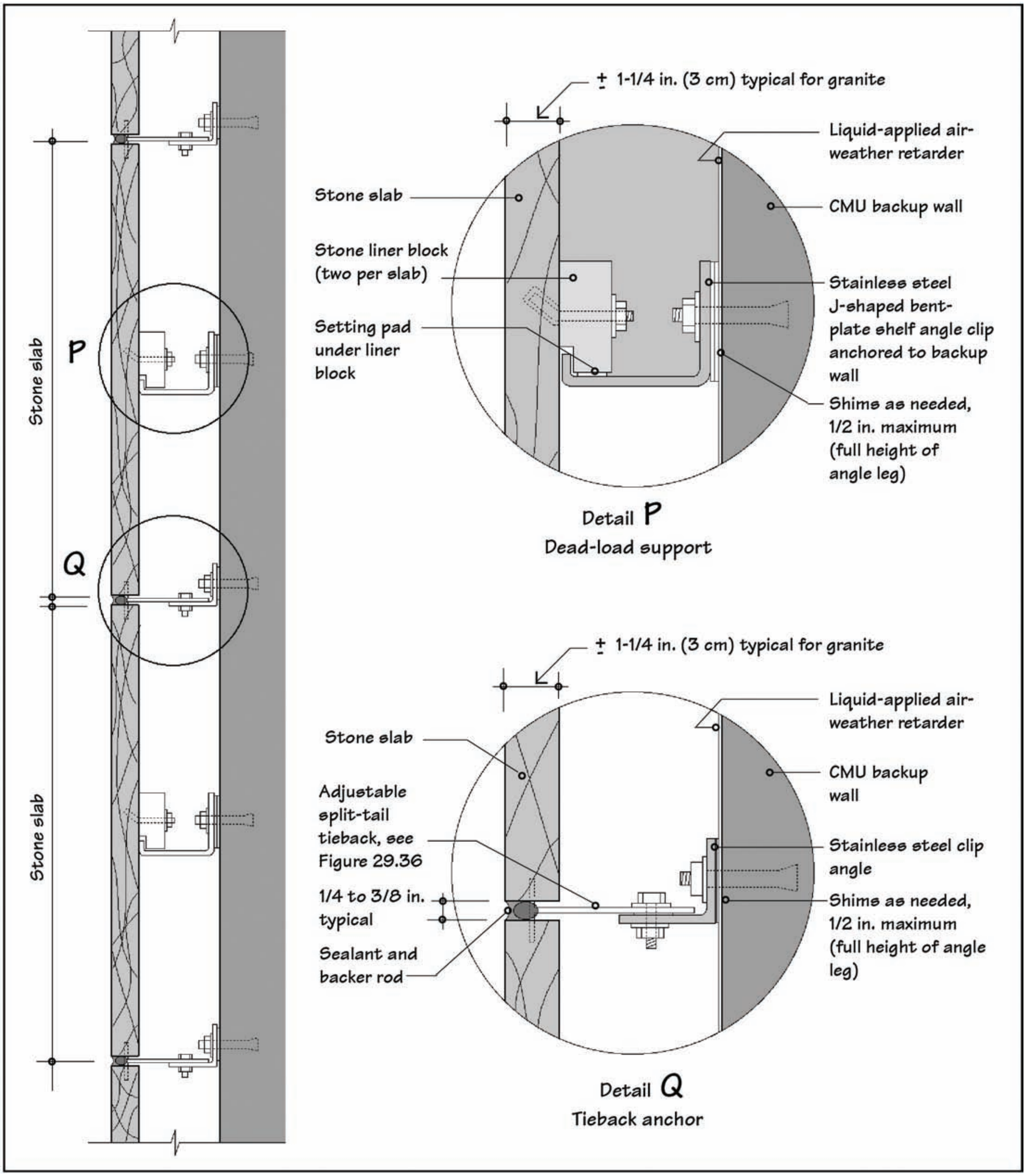

Stone slab
P
Q
Stone slab
± 1-1/4 in. (3 cm) typical for granite
Liquid-applied air-weather retarder
Stone slab
CMU backup wall
Stone liner block (two per slab)
Setting pad under liner block
Stainless steel J-shaped bent-plate shelf angle clip anchored to backup wall
Shims as needed, 1/2 in. maximum (full height of angle leg)
Detail P
Dead-load support
± 1-1/4 in. (3 cm) typical for granite
Liquid-applied air-weather retarder
Stone slab
CMU backup wall
Adjustable split-tail tieback, see Figure 29.36
Stainless steel clip angle
1/4 to 3/8 in. typical
Shims as needed, 1/2 in. maximum (full height of angle leg)
Sealant and backer rod
Detail Q
Tieback anchor

FIGURE 29.33 A section through stone cladding with concrete masonry backup wall using the standard-set method.

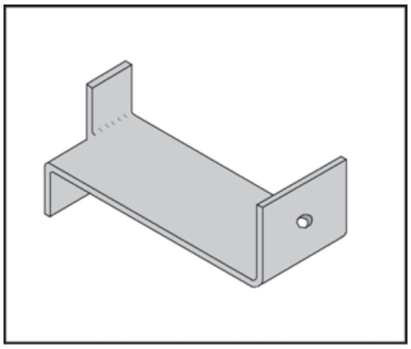


FIGURE 29.34 A typical split-tail anchor.

29.11 FIELD INSTALLATION OF STONE—VERTICAL CHANNEL METHOD

The anchorage of stone slabs is substantially simplified by using continuous vertical support channels, Figure 29.43. The manufacturers of channels provide various accessories to anchor the channels to the backup wall.

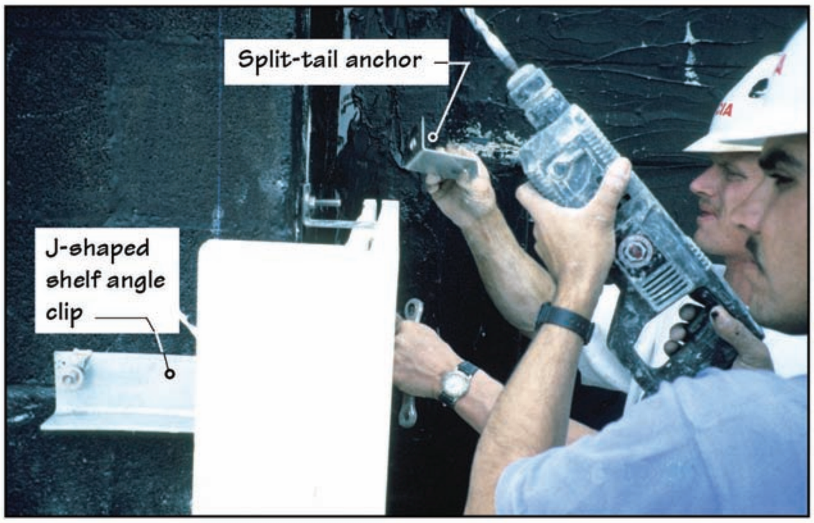

Split-tail anchor
J-shaped shelf angle clip

FIGURE 29.35 A split-tail anchor secured directly to the backup wall.

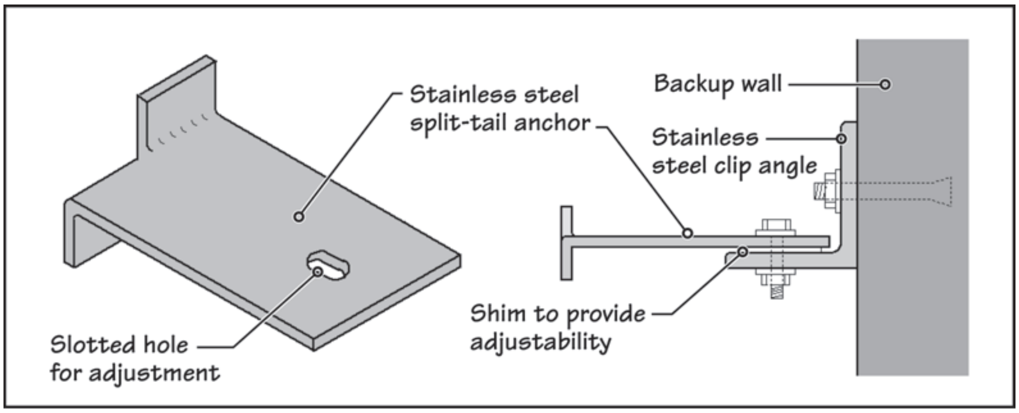

Stainless steel split-tail anchor
Backup wall
Stainless steel clip angle
Slotted hole for adjustment
Shim to provide adjustability

FIGURE 29.36 An adjustable split-tail tieback secured to the backup wall through a clip angle.

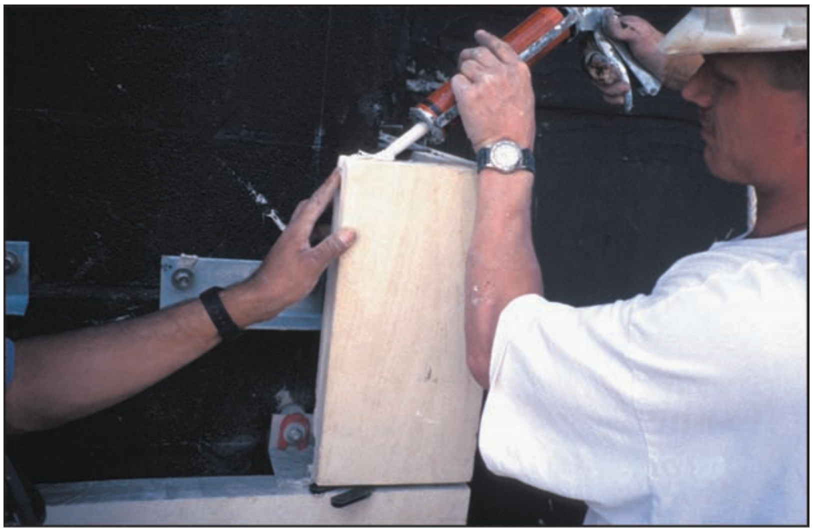


FIGURE 29.37 Applying sealant in kerfs of a stone slab before inserting tiebacks.

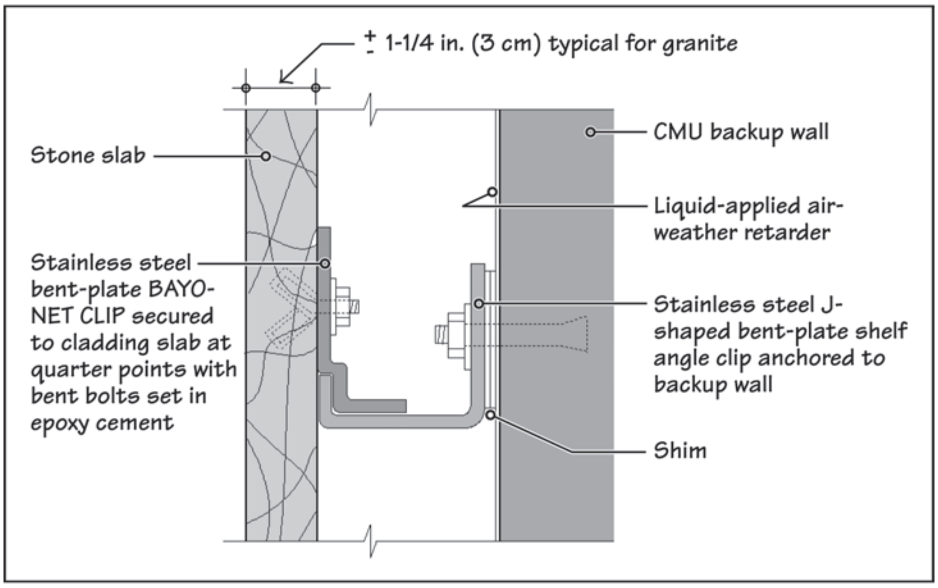

± 1-1/4 in. (3 cm) typical for granite
Stone slab
CMU backup wall
Liquid-applied air-weather retarder
Stainless steel bent-plate BAYO-NET CLIP secured to cladding slab at quarter points with bent bolts set in epoxy cement
Stainless steel J-shaped bent-plate shelf angle clip anchored to backup wall
Shim

FIGURE 29.38 Bayonet anchor clips as an alternative to liner blocks for dead-load supports.

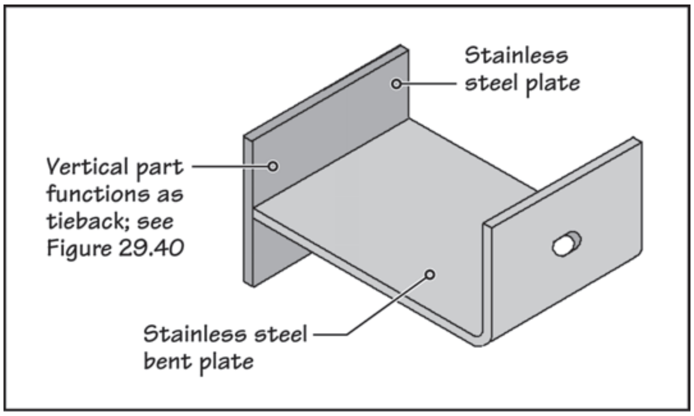

Stainless
steel plate
Vertical part
functions as
tieback; see
Figure 29.40
Stainless steel
bent plate

FIGURE 29.39 A combined dead-load support and tieback anchor formed by welding a stainless steel (flat) plate to a stainless steel bent plate.

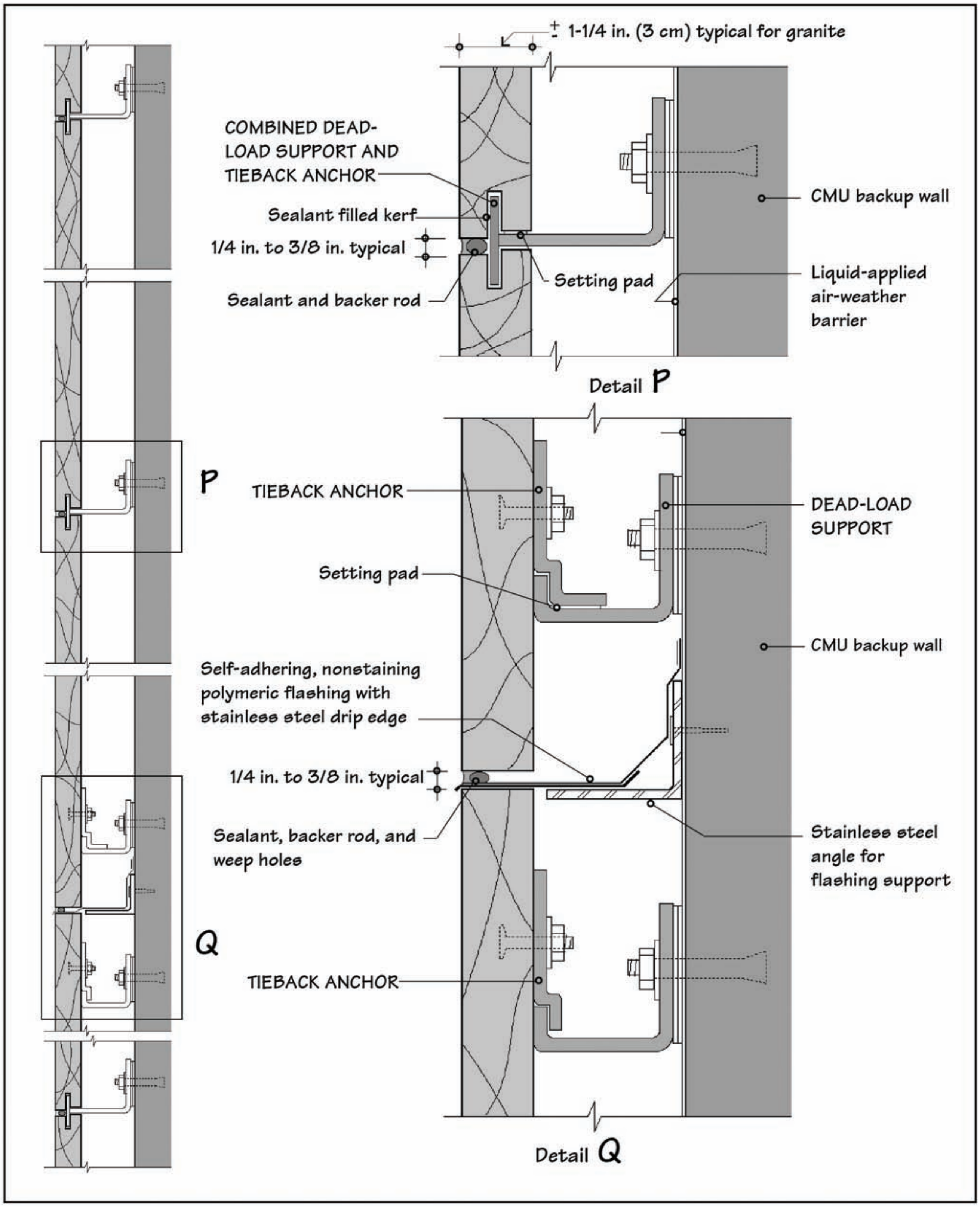

± 1-1/4 in. (3 cm) typical for granite
COMBINED DEAD-
LOAD SUPPORT AND
TIEBACK ANCHOR
Sealant filled kerf
1/4 in. to 3/8 in. typical
Sealant and backer rod
Setting pad
CMU backup wall
Liquid-applied
air-weather
barrier
Detail P
P
TIEBACK ANCHOR
DEAD-LOAD
SUPPORT
Setting pad
CMU backup wall
Self-adhering, nonstaining
polymeric flashing with
stainless steel drip edge
1/4 in. to 3/8 in. typical
Sealant, backer rod, and
weep holes
Stainless steel
angle for
flashing support
Q
TIEBACK ANCHOR
Detail Q

FIGURE 29.40 A typical section through a stone-clad exterior wall using combined dead-load and tieback anchors. Separate dead-load supports and tiebacks have been used at locations of flashing and weep holes.

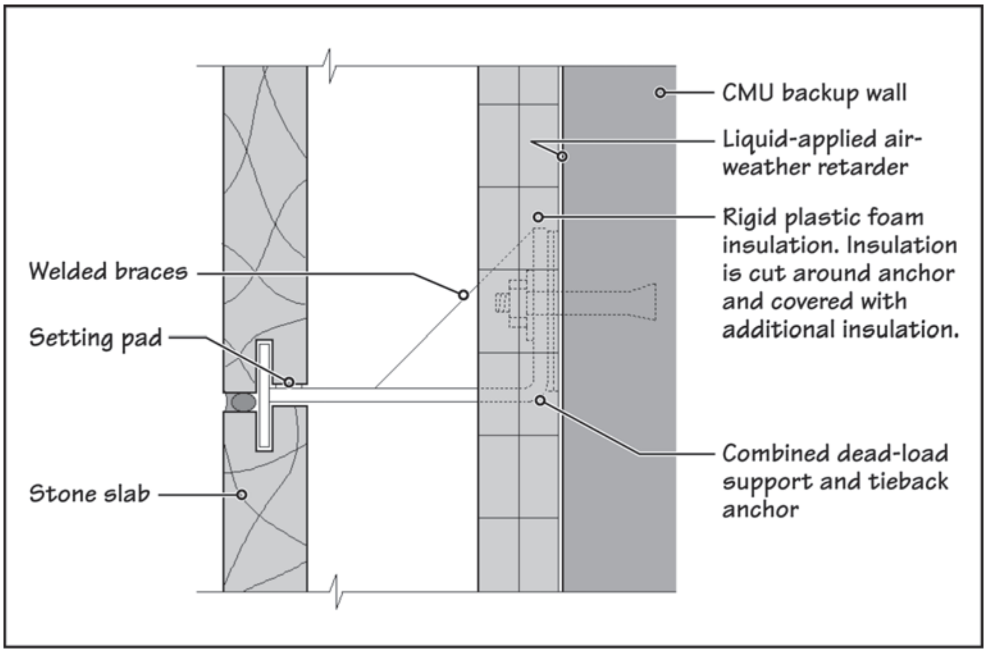

CMU backup wall
Liquid-applied air-weather retarder
Rigid plastic foam insulation. Insulation is cut around anchor and covered with additional insulation.
Welded braces
Setting pad
Combined dead-load support and tieback anchor
Stone slab

FIGURE 29.41 An alternative to Detail P in Figure 29.40.

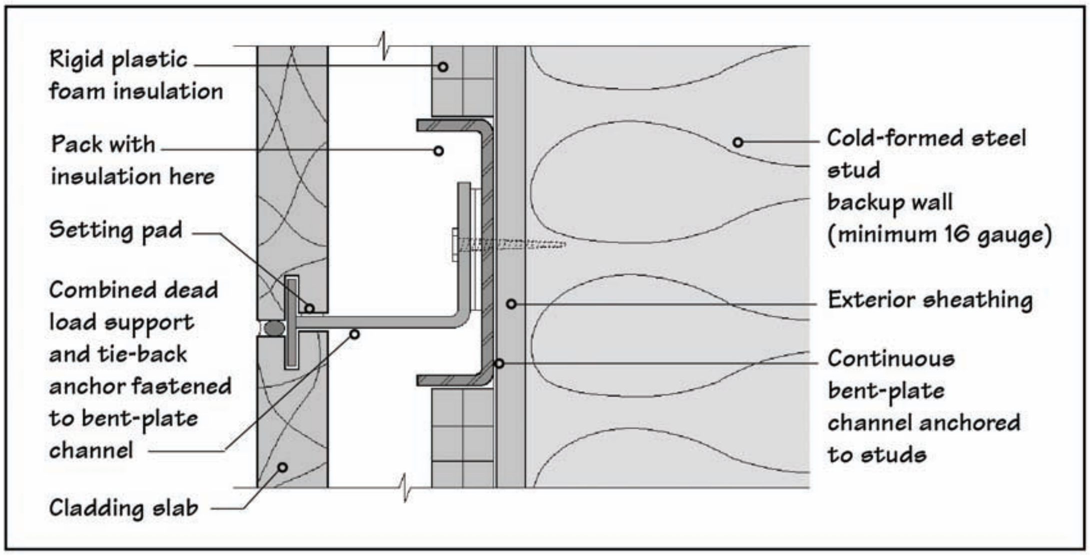

Rigid plastic foam insulation
Pack with insulation here
Setting pad
Combined dead load support and tie-back anchor fastened to bent-plate channel
Cladding slab
Cold-formed steel stud backup wall (minimum 16 gauge)
Exterior sheathing
Continuous bent-plate channel anchored to studs

FIGURE 29.42 A typical stone cladding detail with a steel-stud backup wall.

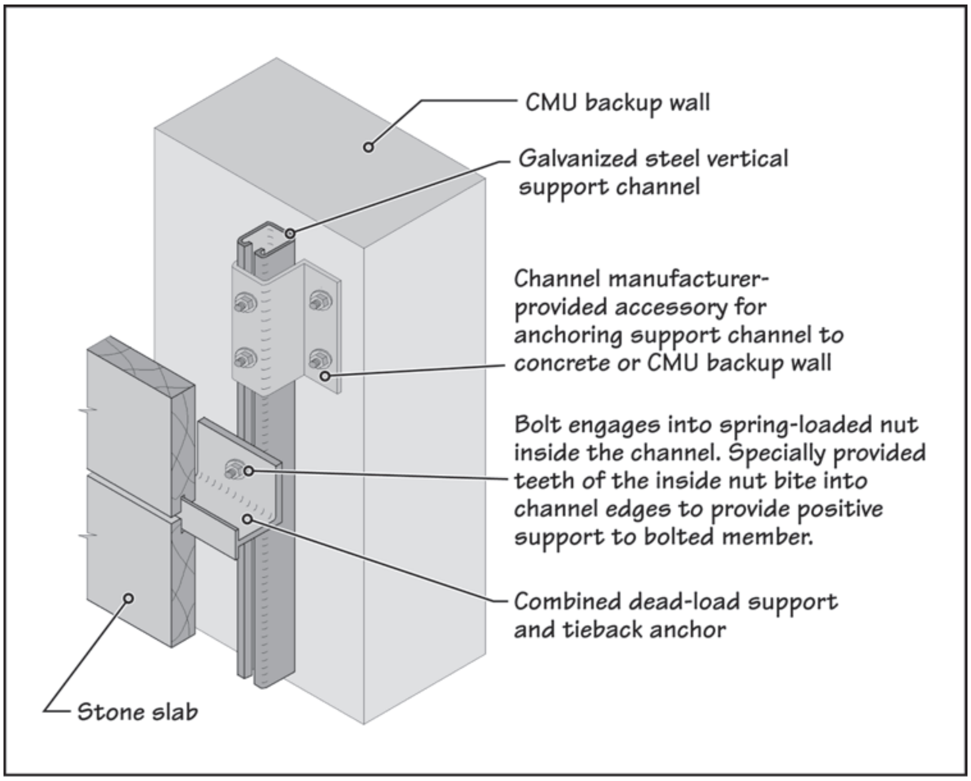

CMU backup wall
Galvanized steel vertical support channel
Channel manufacturer-provided accessory for anchoring support channel to concrete or CMU backup wall
Bolt engages into spring-loaded nut inside the channel. Specially provided teeth of the inside nut bite into channel edges to provide positive support to bolted member.
Combined dead-load support and tieback anchor
Stone slab

FIGURE 29.43 Adjustable anchorage of a vertical channel to a concrete or CMU backup wall; see also Figure 29.44.

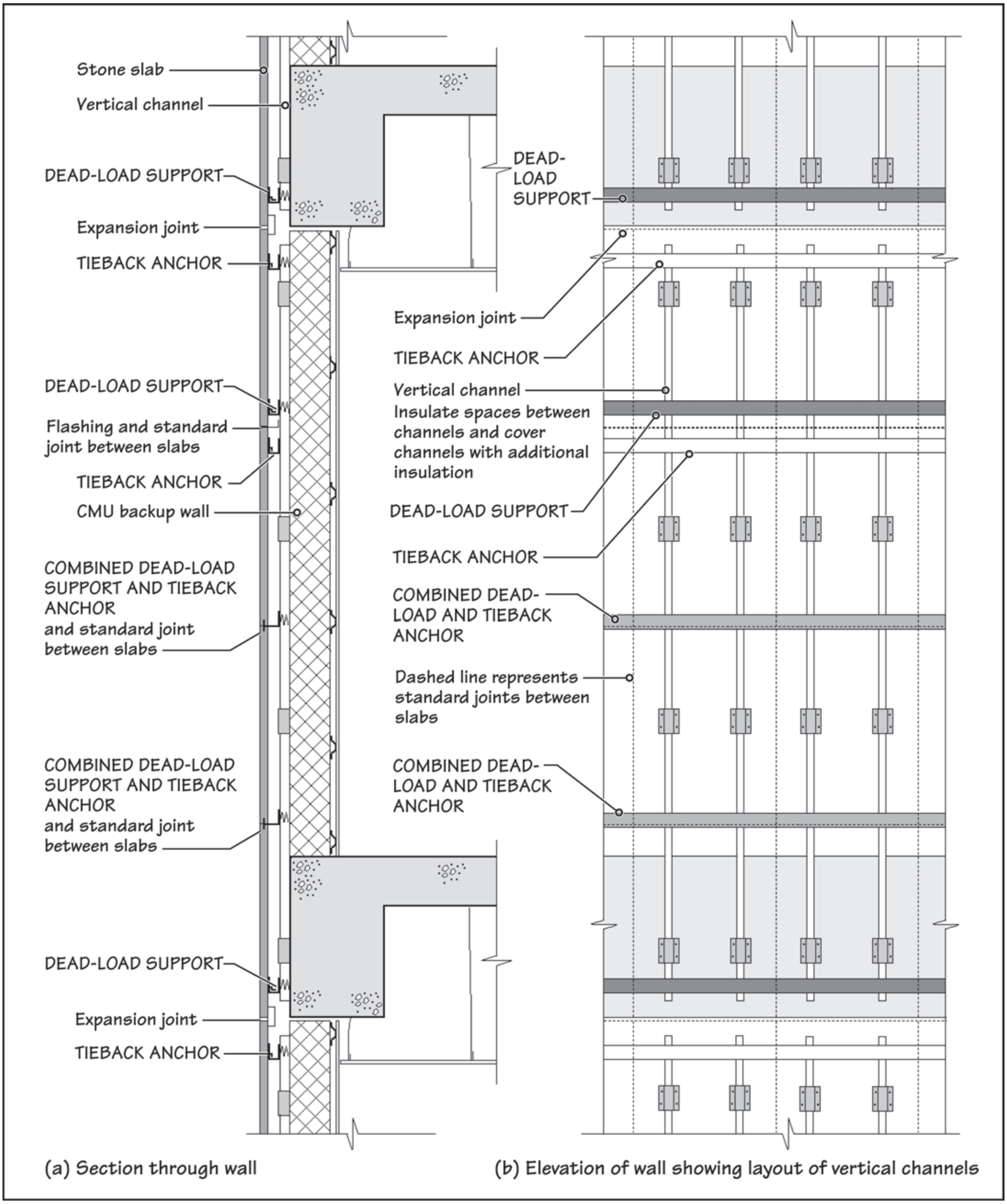

Stone slab
Vertical channel
DEAD-LOAD SUPPORT
Expansion joint
TIEBACK ANCHOR
DEAD-LOAD SUPPORT
Flashing and standard joint between slabs
TIEBACK ANCHOR
CMU backup wall
COMBINED DEAD-LOAD SUPPORT AND TIEBACK ANCHOR and standard joint between slabs
COMBINED DEAD-LOAD SUPPORT AND TIEBACK ANCHOR and standard joint between slabs
DEAD-LOAD SUPPORT
Expansion joint
TIEBACK ANCHOR
DEAD-LOAD SUPPORT
Expansion joint
TIEBACK ANCHOR
Vertical channel
Insulate spaces between channels and cover channels with additional insulation
DEAD-LOAD SUPPORT
TIEBACK ANCHOR
COMBINED DEAD-LOAD AND TIEBACK ANCHOR
Dashed line represents standard joints between slabs
COMBINED DEAD-LOAD AND TIEBACK ANCHOR
(a) Section through wall
(b) Elevation of wall showing layout of vertical channels

FIGURE 29.44 A typical section and elevation showing the anchorage of stone cladding using the vertical support channels shown in Figure 29.43.

The channels are spaced at quarter points of the slabs and extend from floor to floor, with breaks at each floor level, Figure 29.44. With a CMU backup wall, the support channels are anchored directly to it, as shown in Figure 29.43. With a steel-stud backup wall, a continuous galvanized steel plate is fastened to the studs at suitable intervals, to which the channels are anchored, Figure 29.45.

Where a short length of stone return (e.g., at a soffit) is required, it is obtained through the use of stainless steel clip angles bolted to slabs, Figure 29.46.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

25. The dead-load supports for each stone slab (in a stone-clad wall) are generally
- **a.** two, placed in the center of the slab, one above the other.
- **b.** two, placed at the same level at one-third points.
- **c.** three, placed at the same level at one-third points.
- **d.** two, placed at the same level at quarter points.
- **e.** four, placed at the same level at quarter points.

26. A bayonet clip in the stone cladding industry refers to
- **a.** dead-load support.
- **b.** lateral-load support.
- **c.** flashing retainer.
- **d.** none of the above.

27. A combined dead-load and lateral-load support anchor for stone cladding consists of
- **a.** a stainless steel L-shaped bent plate.
- **b.** a stainless steel J-shaped bent plate.
- **c.** a stainless steel H-shaped bent plate.
- **d.** a stainless steel L-shaped bent plate welded to a stainless steel flat plate.
- **e.** none of the above.

28. The term *kerf* in stone cladding industry refers to
- **a.** a slot in a stone slab.
- **b.** dead-load support for a stone slab.
- **c.** a tieback anchor for a stone slab.
- **d.** none of the above.

29. When vertical support channels are used in stone cladding, dead-load supports and tiebacks are not required for stone slabs.
- **a.** True
- **b.** False

30. The thickness of granite used in wall cladding is generally
- **a.** $1\frac{1}{4}$ in.
- **b.** $1\frac{1}{2}$ in.
- **c.** 2 in.
- **d.** $2\frac{1}{4}$ in.
- **e.** none of the above.

29.12 THIN STONE CLADDING

Another form of panelized stone cladding uses an extremely thin (nearly $\frac{1}{4}$ in. thick) stone veneer bonded to an aluminum honeycomb backing. The panels are manufactured by epoxy-cementing aluminum honeycomb on both sides of an approximately $\frac{3}{4}$-in.-thick stone slab (generally granite or marble). The honeycomb-stone-honeycomb combination is sawn through the middle, producing two identical panels, Figure 29.47.

After sawing, the stone facing on each panel is finished as needed (e.g., polished, honed, abrasive-blasted, and bush-hammered). The honeycomb backing is $\frac{3}{4}$ in. thick, giving an overall finished panel thickness of approximately 1 in. (For a panel intended for interior use, e.g., for lining the walls of elevator lobbies, foyers, and ceilings, the honeycomb backing is only $\frac{3}{8}$ in. thick.)

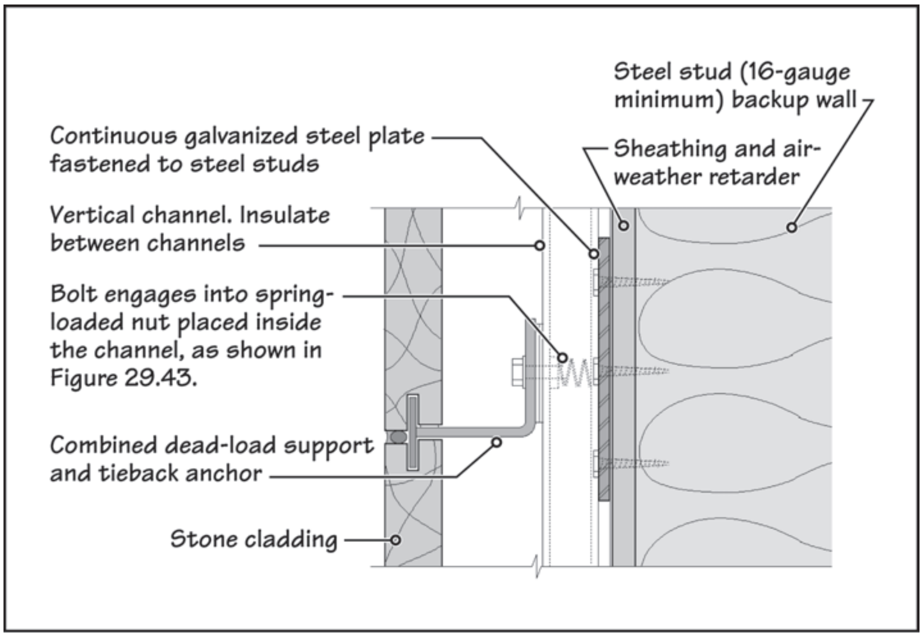

Steel stud (16-gauge minimum) backup wall
Continuous galvanized steel plate fastened to steel studs
Sheathing and air-weather retarder
Vertical channel. Insulate between channels
Bolt engages into spring-loaded nut placed inside the channel, as shown in Figure 29.43.
Combined dead-load support and tieback anchor
Stone cladding

FIGURE 29.45 Anchorage of a vertical channel to a steel-stud backup wall.

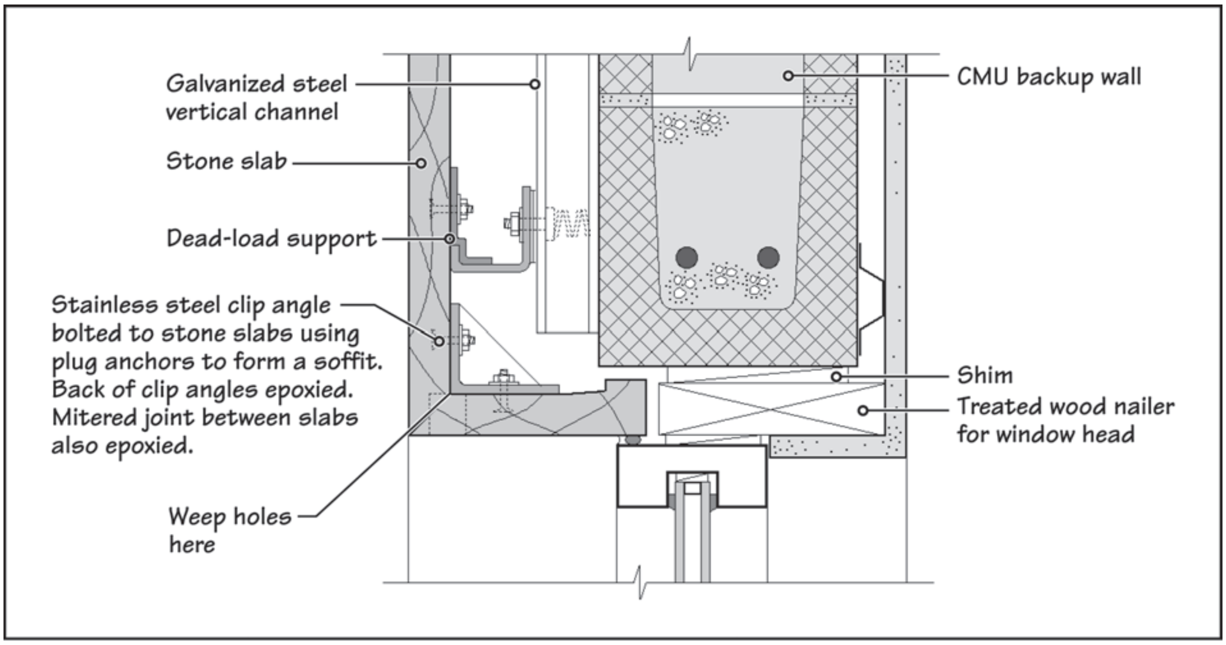

Galvanized steel vertical channel
CMU backup wall
Stone slab
Dead-load support
Stainless steel clip angle bolted to stone slabs using plug anchors to form a soffit. Back of clip angles epoxied. Mitered joint between slabs also epoxied.
Shim
Treated wood nailer for window head
Weep holes here

FIGURE 29.46 One of the several ways of detailing a stone-clad wall to create a return (soffit) at a window head.

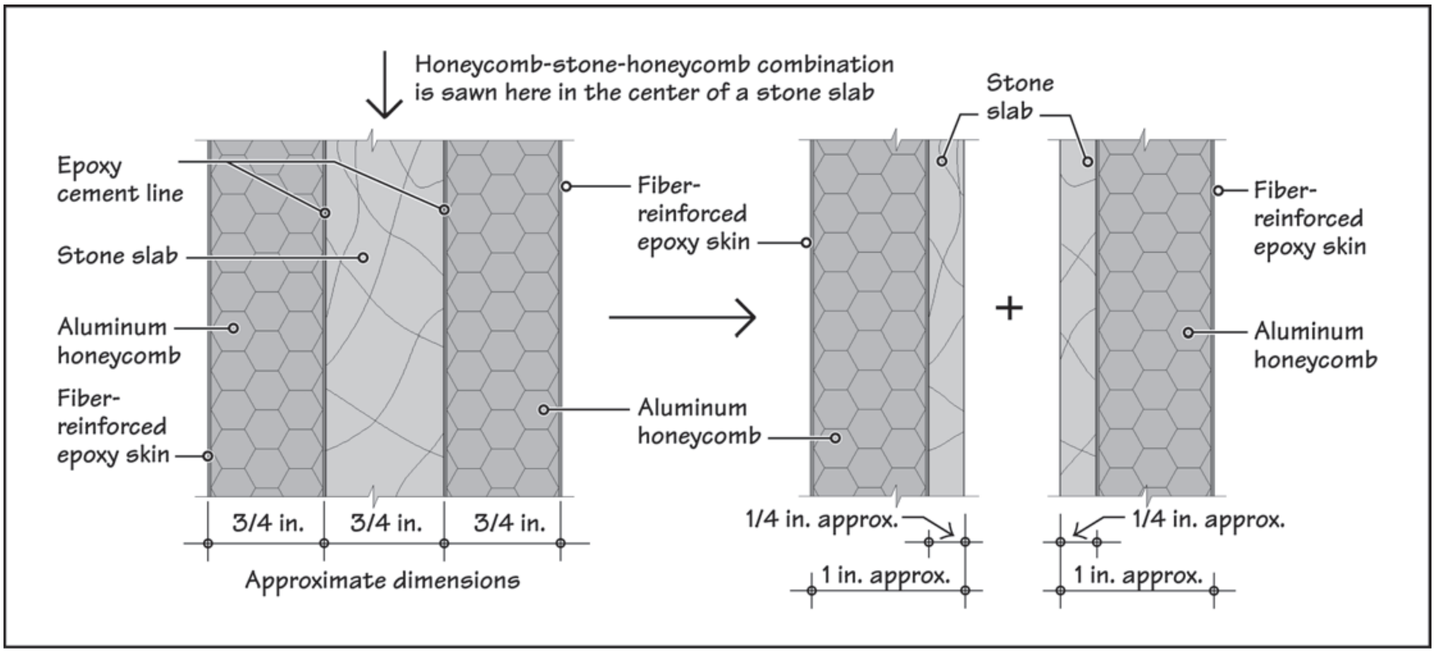

Honeycomb-stone-honeycomb combination is sawn here in the center of a stone slab
Epoxy cement line
Stone slab
Aluminum honeycomb
Fiber-reinforced epoxy skin
Fiber-reinforced epoxy skin
Aluminum honeycomb
3/4 in.
3/4 in.
3/4 in.
Approximate dimensions
Stone slab
+
Fiber-reinforced epoxy skin
Aluminum honeycomb
1/4 in. approx.
1 in. approx.
1/4 in. approx.
1 in. approx.

FIGURE 29.47 Making of a thin stone panel.

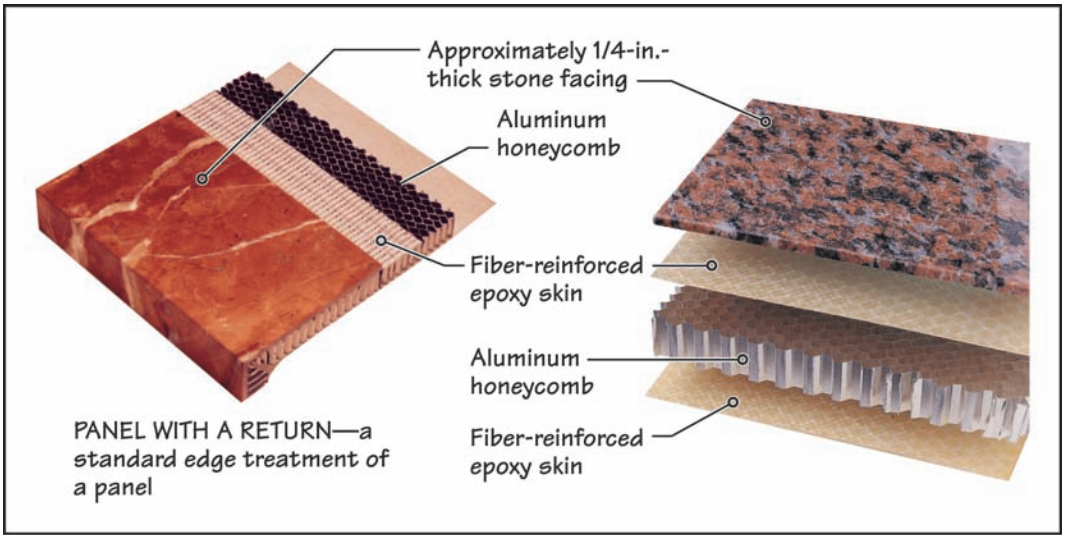

Approximately 1/4-in.-thick stone facing
Aluminum honeycomb
Fiber-reinforced epoxy skin
Aluminum honeycomb
Fiber-reinforced epoxy skin
PANEL WITH A RETURN—a standard edge treatment of a panel

FIGURE 29.48 Anatomy of a stone-honeycomb panel showing the standard treatment of its exposed edge. (Photos courtesy of Stone Panels Inc.)

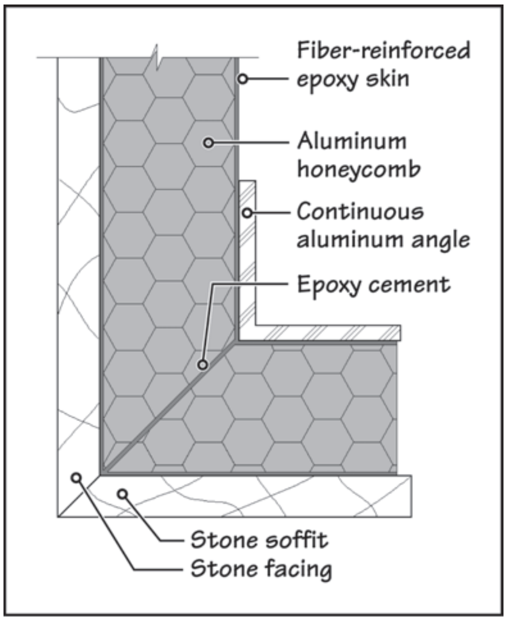

Fiber-reinforced epoxy skin
Aluminum honeycomb
Continuous aluminum angle
Epoxy cement
Stone soffit
Stone facing

FIGURE 29.49 Anatomy of a stone-honeycomb panel with a deep soffit.

The standard treatment on an exposed edge of the panel is a small return, as shown in Figure 29.48. Where a larger return is required (e.g., to obtain a deeper soffit at a window head), it is obtained by cementing a continuous aluminum angle to the honeycomb, Figure 29.49.

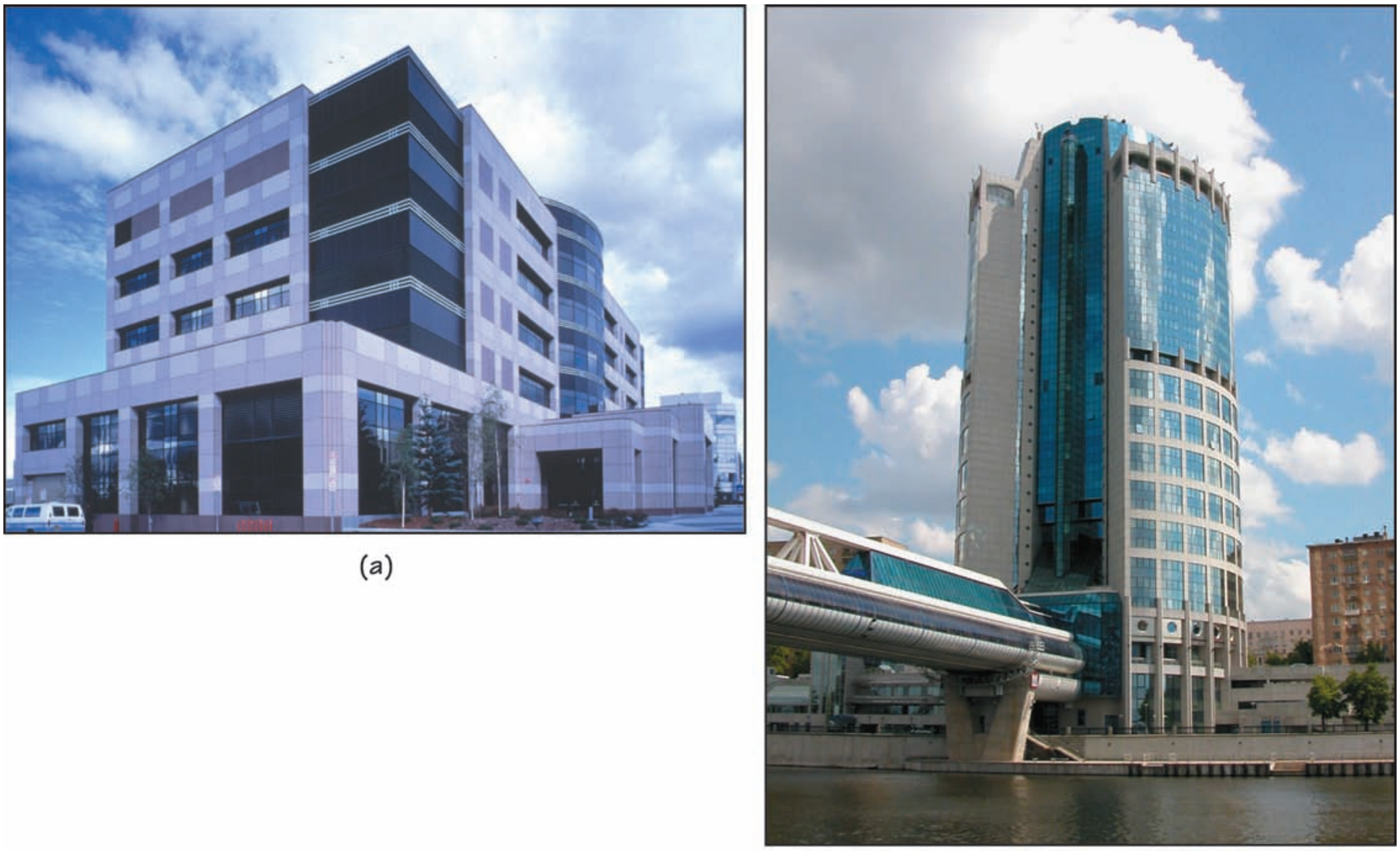
The standard size of the panels is 4 ft × 8 ft, but other sizes are available, with a maximum of 5 ft × 10 ft. The light weight of the panels makes their installation convenient, particularly in high-labor areas. A 1-in.-thick stone-honeycomb panel weighs only 3.3 psf, which is approximately the weight of $\frac{1}{4}$-in.-thick glass.

The bending strength of a stone-honeycomb panel is fairly high because of the honeycomb backing and the fiber-reinforced epoxy skin bonded to it. The composition also gives a great deal of ductility to the panel so that it is able to flex under lateral loads.

The panels' light weight, high ductility, and bending strength make it ideal for use in seismic areas, where the aesthetics of natural stone cladding without its heavy weight are required. These are some of the reasons cited for their use in the courthouse in Anchorage, Alaska, and the International Business Center, Moscow, Russia, Figure 29.50.

ANCHORAGE OF STONE-HONEYCOMB PANELS

The most commonly used method of anchoring the panels to the steel-stud, concrete, or concrete masonry backup wall uses two continuous interlocking channels.


(a)

(b)

FIGURE 29.50 Examples of buildings with stone-honeycomb exterior wall cladding. **(a)** Courthouse, Anchorage, Alaska. **(b)** International Business Center, Moscow, Russia. (Photos courtesy of Stone Panels Inc.)

One of these channels is shop installed to the back of the panel, and the other channel is field anchored to the backup wall, Figure 29.51. Figure 29.52 shows a typical detail of the use of the panels in a building.

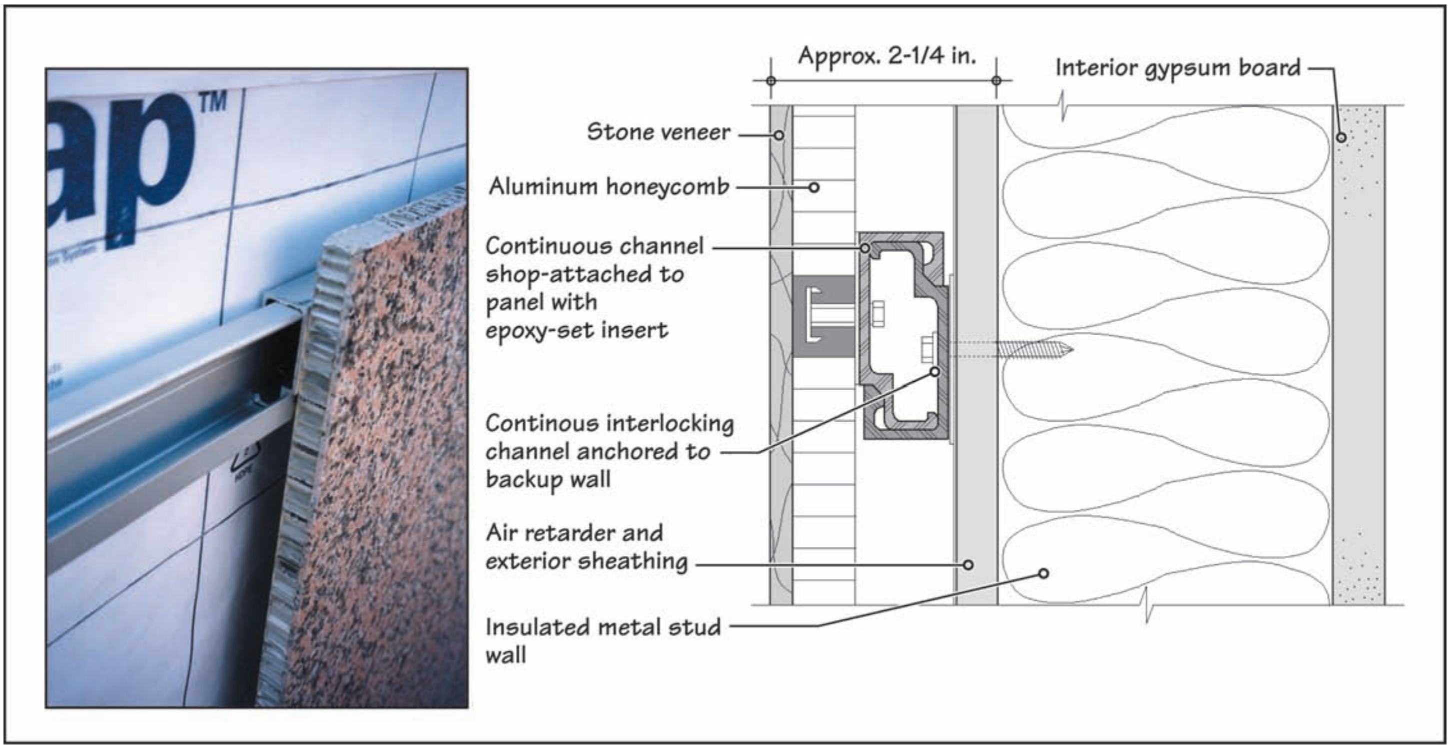

ap™
Approx. 2-1/4 in.
Interior gypsum board
Stone veneer
Aluminum honeycomb
Continuous channel shop-attached to panel with epoxy-set insert
Continous interlocking channel anchored to backup wall
Air retarder and exterior sheathing
Insulated metal stud wall

FIGURE 29.51 A commonly used method of anchoring stone-honeycomb panels to a steel-stud backup wall.

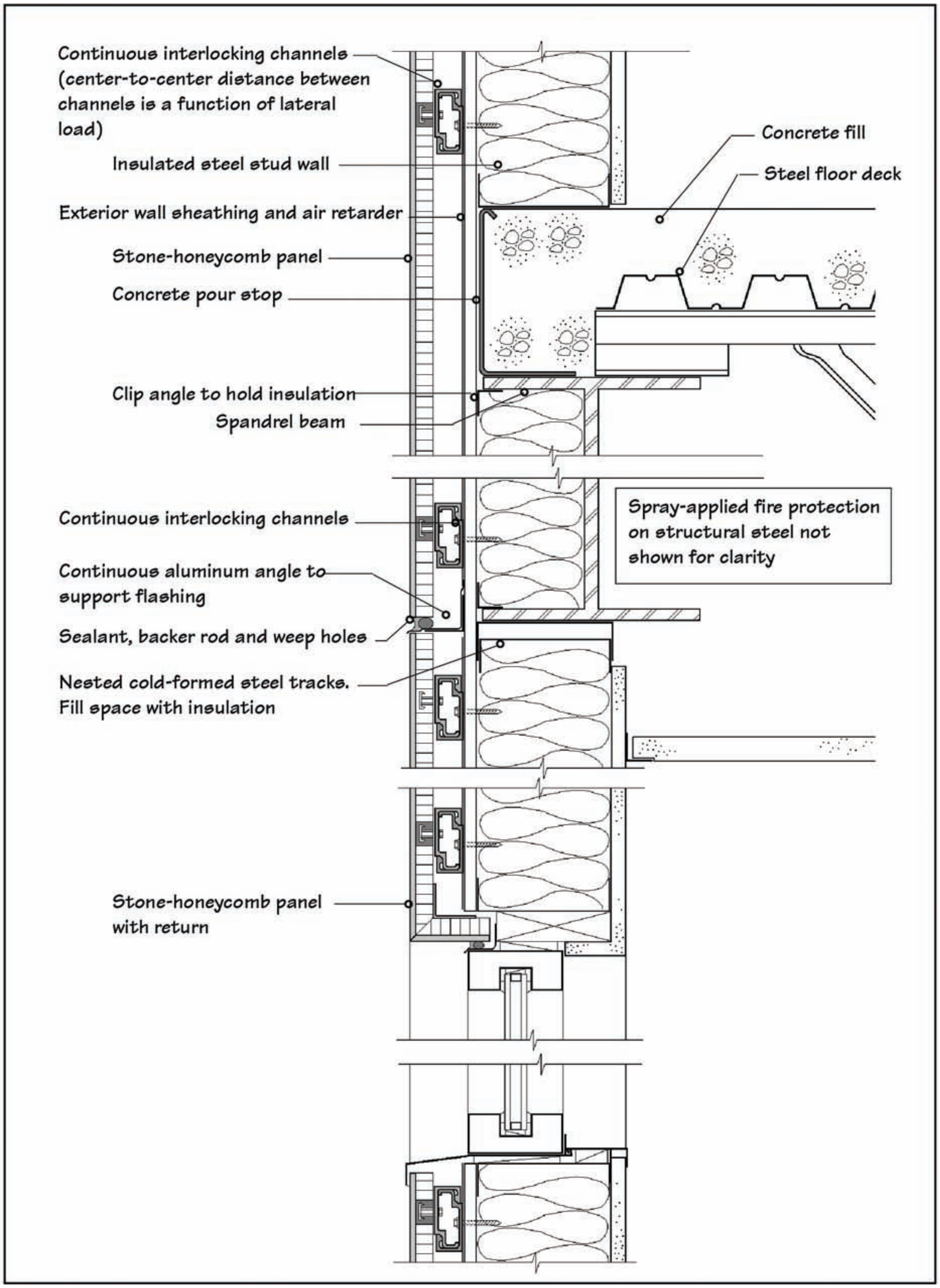

Continuous interlocking channels (center-to-center distance between channels is a function of lateral load)
Insulated steel stud wall
Exterior wall sheathing and air retarder
Stone-honeycomb panel
Concrete pour stop
Clip angle to hold insulation
Spandrel beam
Concrete fill
Steel floor deck
Continuous interlocking channels
Continuous aluminum angle to support flashing
Sealant, backer rod and weep holes
Nested cold-formed steel tracks. Fill space with insulation
Spray-applied fire protection on structural steel not shown for clarity
Stone-honeycomb panel with return

FIGURE 29.52 A typical wall section through a steel-frame building clad with stone-honeycomb panels.

PREFABRICATED STONE-HONEYCOMB CURTAIN WALL PANELS

Stone-honeycomb panels can also be prefabricated into curtain wall panels, which generally extend from column to column and are hung from the building's structure like other curtain wall panels.

29.13 INSULATED METAL PANELS

Another lightweight exterior cladding system consists of metal (typically steel) panels with 2-in. to 3-in. factory-installed polyurethane foam insulation between metal skins. The panels are available factory painted in various colors, in galvanized steel, and in stainless steel.

Several surface finishes, such as smooth, embossed, and a precast concrete-like texture, are available.

Because of the insulating core, the panels have a high R-value. Therefore, additional insulation in the wall may not be needed. The joinery between panels has been perfected by manufacturers to provide concealed fasteners and variable joint widths, Figure 29.53.

The panels weigh less than 3 psf and are available in widths of 2–4 ft and in lengths of up to approximately 30 ft. They can be installed horizontally on a metal-stud wall or vertically from spandrel beam to spandrel beam with intermediate horizontal supports. When they are installed over a metal-stud wall, the exterior sheathing may be omitted because the panels provide a weather barrier. The panels can be integrated with windows and other openings with manufacturer-provided accessories and detailing assistance, Figure 29.54.

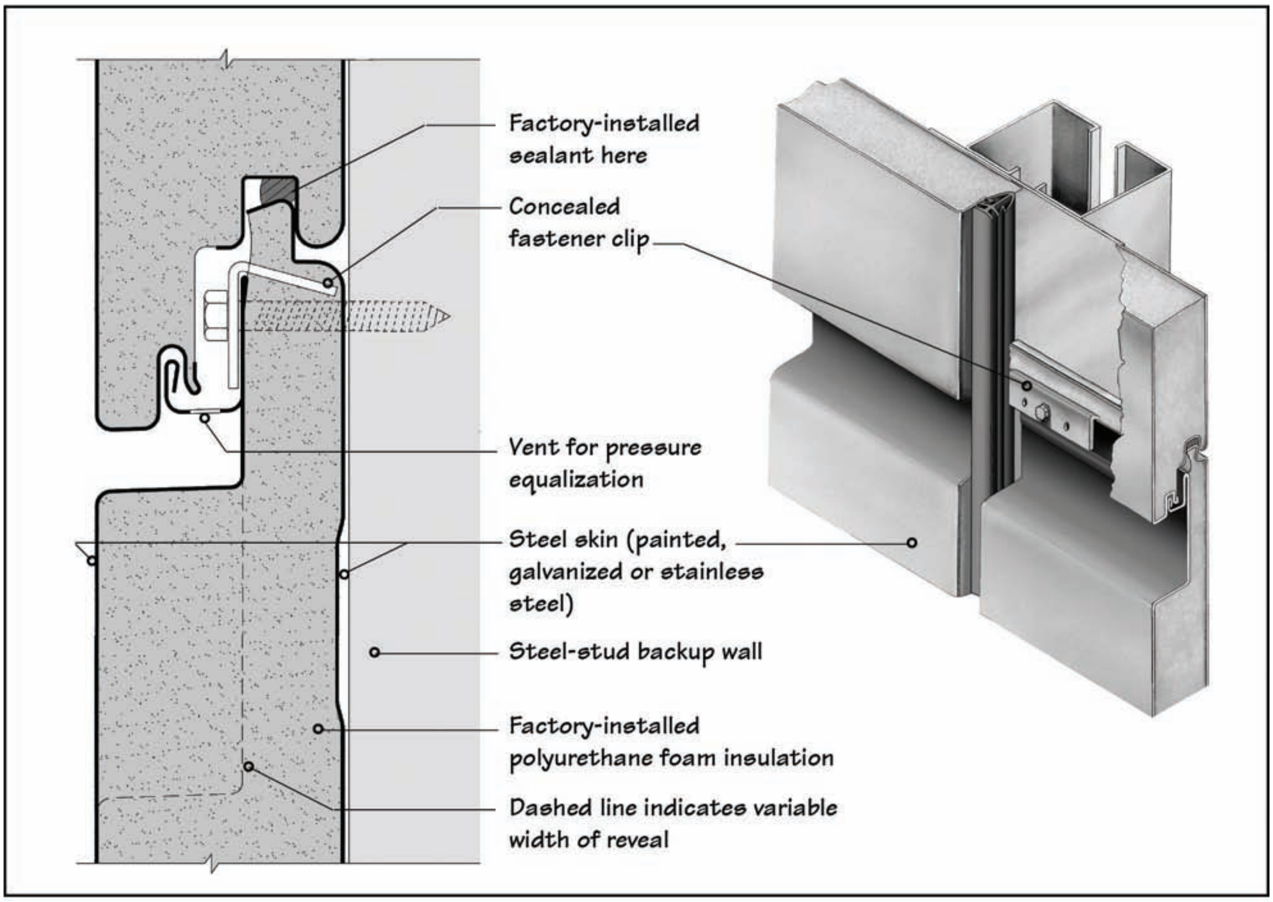

Factory-installed sealant here
Concealed fastener clip
Vent for pressure equalization
Steel skin (painted, galvanized or stainless steel)
Steel-stud backup wall
Factory-installed polyurethane foam insulation
Dashed line indicates variable width of reveal

FIGURE 29.53 A section and a cutaway section showing the anatomy of a typical insulated metal panel. (Images courtesy of Centria Architectural Systems, Inc.)

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

31. In a stone-honeycomb wall cladding panel, the thickness of the stone is approximately
a. 1 in.
b. $\frac{3}{4}$ in.
c. $\frac{1}{2}$ in.
d. $\frac{1}{4}$ in.
e. $\frac{1}{8}$ in.

32. In a stone-honeycomb wall cladding panel, the honeycomb is generally made of
a. stainless steel.
b. aluminum.
c. titanium.
d. copper.
e. none of the above.

33. A stone-honeycomb panel is anchored to the backup wall using
a. epoxy cement.
b. separate dead-load supports and tiebacks.
c. two interlocking metal channels.
d. stainless steel bolts.

34. In an insulated wall metal panel, the insulation is sandwiched between
a. a metal sheet in the front and a fiberglass scrim at the back of the panel.
b. a metal sheet on both sides.
c. a metal sheet in the front and an acrylic sheet at the back of the panel.
d. none of the above.

35. The weight of insulated metal panels and stone-honeycomb panels is approximately the same.
a. True
b. False

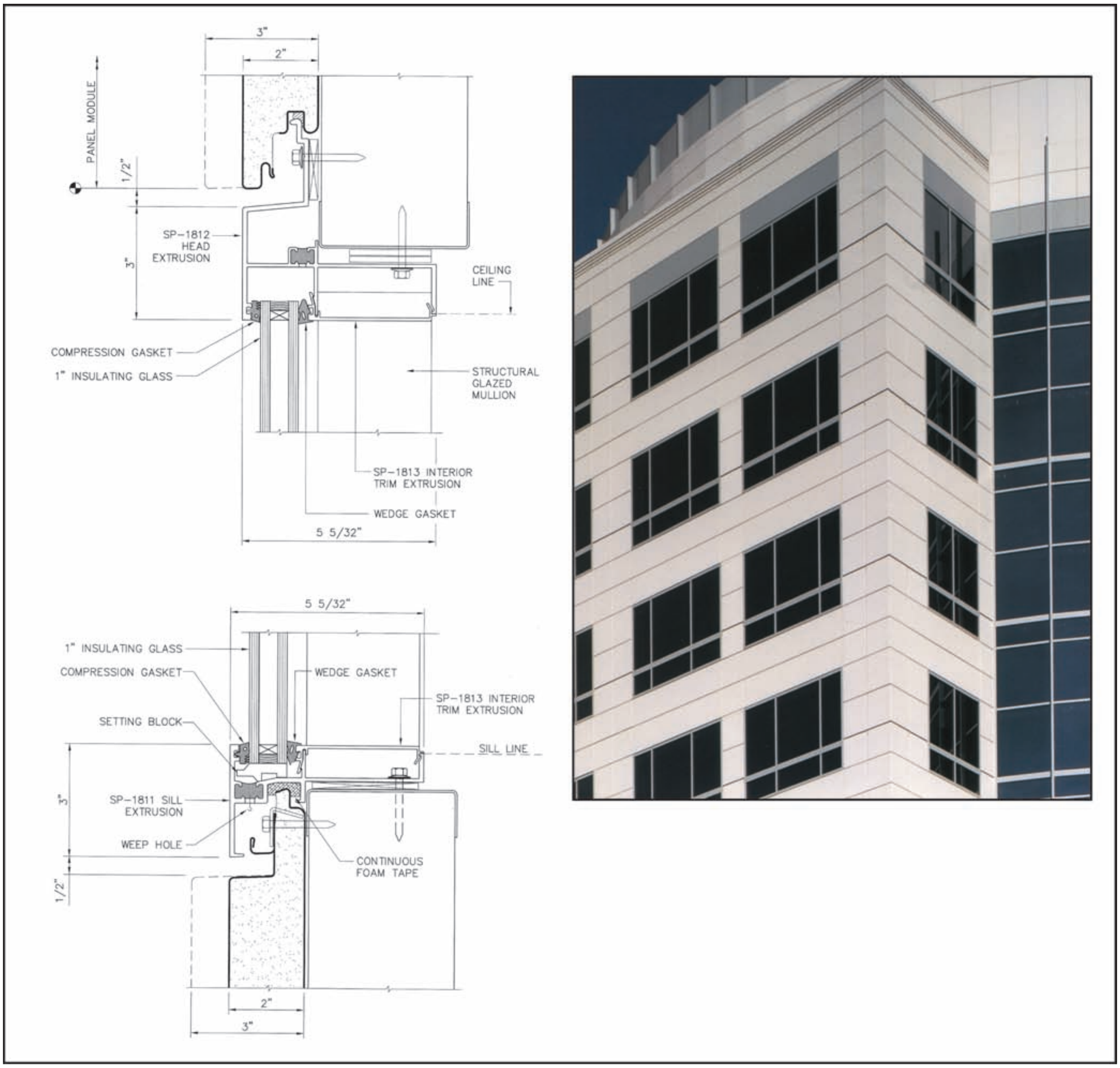

3"
2"
PANEL MODULE
1/2"
SP-1812 HEAD EXTRUSION
3"
CEILING LINE
COMPRESSION GASKET
1" INSULATING GLASS
STRUCTURAL GLAZED MULLION
SP-1813 INTERIOR TRIM EXTRUSION
WEDGE GASKET
5 5/32"
5 5/32"
1" INSULATING GLASS
COMPRESSION GASKET
WEDGE GASKET
SP-1813 INTERIOR TRIM EXTRUSION
SETTING BLOCK
SILL LINE
3"
SP-1811 SILL EXTRUSION
WEEP HOLE
CONTINUOUS FOAM TAPE
1/2"
2"
3"

FIGURE 29.54 Insulated metal panels and their integration with windows and other openings as per manufacturer-provided details and accessories. (Photo and details courtesy of Centria Architectural Systems, Inc.)

REVIEW QUESTIONS

1. Using a sketch, explain the anatomy of stucco applied over a metal-stud wall assembly, showing all components.
2. What are the essential differences between stucco applied on a stud wall and that applied on a CMU wall?
3. Discuss the difference between control joints and expansion joints in a stucco-clad wall.
4. Explain the difference between PB EIFS and PM EIFS. Which of the two methods is more commonly used?
5. With the help of a sketch, illustrate the anatomy of PB EIFS. Also, explain what backwrapping is and where it is used in EIFS cladding.
6. Discuss the pros and cons of EIFS cladding compared with stucco cladding.
7. Sketch a split-tail anchor, showing the material it is made of and its function in a stone-clad wall.
8. Sketch a dead-load support of stone cladding with a bayonet clip.
9. Sketch a combined dead-load support and tieback anchor used in a stone-clad wall.
10. Explain the anatomy of a stone-honeycomb panel. With the help of a sketch, explain how the panels are anchored to a backup wall.

CHAPTER

30

Glass, Glazing, and Light-Transmitting Plastics

CHAPTER OUTLINE

30.1 MANUFACTURE OF FLAT GLASS

30.2 TYPES OF HEAT-MODIFIED GLASS

30.3 GLASS AND SOLAR RADIATION

30.4 TYPES OF TINTED AND REFLECTIVE GLASS

30.5 GLASS AND LONG-WAVE RADIATION

30.6 INSULATING GLASS UNIT (IGU)

30.7 R-VALUE (OR U-VALUE) OF GLASS

30.8 GLASS AND GLAZING

30.9 SAFETY GLASS

30.10 LAMINATED GLASS

30.11 STRUCTURAL PERFORMANCE OF GLASS

30.12 FIRE-RESISTANT GLASS

30.13 PLASTIC GLAZING

30.14 GLASS FOR SPECIAL PURPOSES

30.15 CRITERIA FOR THE SELECTION OF GLASS

30.16 ANATOMY OF A GLAZING POCKET

PRINCIPLES IN PRACTICE: IMPORTANT FACTS ABOUT RADIATION

PRINCIPLES IN PRACTICE: CONDENSATION-RESISTANCE FACTOR

The introduction of daylight into buildings has always been an important design requirement. In early buildings, this requirement was satisfied by providing voids in walls. Subsequently, in an effort to control daylight, ventilation, and security, windows with wood shutters were developed. The use of oiled-paper panels or muslin cloth in wooden frames, which provided some light without opening the windows, was the next step in providing transparency in buildings.

With the discovery of glass, the window's performance (as well as its appearance) changed dramatically. It was now possible to obtain daylight effectively without admitting other environmental elements, such as wind, rain, dust, and insects. The earliest use of glass in openings is usually traced to the Roman Empire, where it was employed in small sizes.

The first significant use of glass, however, occurred during the Middle Ages as stained glass windows gained popularity in churches. Staining (or painting) of the glass was used as decoration to hide defects such as air bubbles and colored impurities, which were integral to the glass made at that time. During the Middle Ages, church windows were particularly large. They not only provided daylight, but also used dramatic pictures made from brightly stained glass to explain biblical stories to people who could not read.

The transparency of glass improved greatly with the perfection of the *crown glass process* around the fourteenth century [Ref. 30.1]. This method provided glass with fewer air bubbles and other defects. In this process, molten glass was first converted to a globe by blowing through a long pipe, then transferring the globe from the blow pipe to a rod, and subsequently cutting the globe open. The cut globe was finally flattened into a disc by repeated heating and vigorous spinning, Figure 30.1.

In a similar process, called the *cylindrical process*, molten glass was first blown into a globe and subsequently enlarged into a cylinder by swinging the pipe back and forth. The cylinder was later cut along its length, flattened by heating, and converted to sheets, Figure 30.2.

Clear glass, as we know it today, came into commercial use at the end of the seventeenth century with the invention of the glassmaking process by Bernard Perrot [Ref. 30.2]. In Perrot's process, molten ingredients of glass were first cast in a mold and later spread into sheets by rollers. When the glass solidified fully, it was ground and polished on both sides with abrasives. The mechanization of the rolling and grinding operations brought down the price of glass sufficiently so that it could be used commercially in mirrors and storefronts. Although the process of manufacturing modern glass is substantially different from that of the cast or cylindrical glass of several centuries ago, the ingredients are virtually the same.

The transparency of glass, coupled with modern manufacturing techniques that provide large sheets of glass inexpensively, is responsible for the extensive use of glass in modern buildings. These developments have also led to the use of glass as the primary material for the cladding of many building types, Figures 30.3 and 30.4.

In this chapter, the modern process of manufacturing glass, as well as its various types and their properties, are described. Also discussed are light-transmitting plastics, which are sometimes used in lieu of glass.

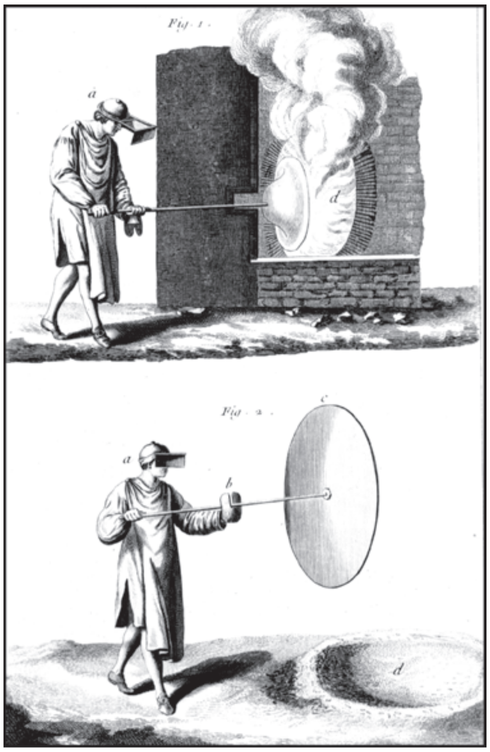


FIGURE 30.1 Crown glassmaking process. (Courtesy of the Collection of the Rakow Research Library, The Corning Museum of Glass, Corning, NY.)

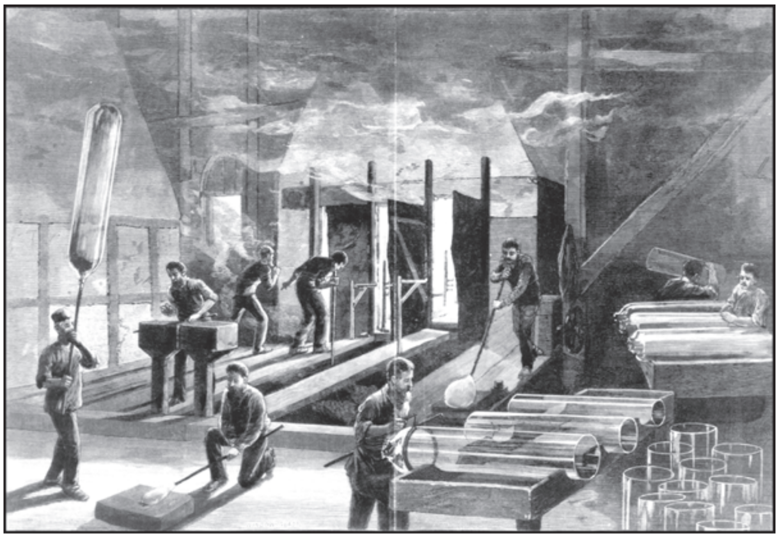


FIGURE 30.2 Cylindrical glassmaking process. (Courtesy of the Collection of the Rakow Research Library, The Corning Museum of Glass, Corning, NY.)

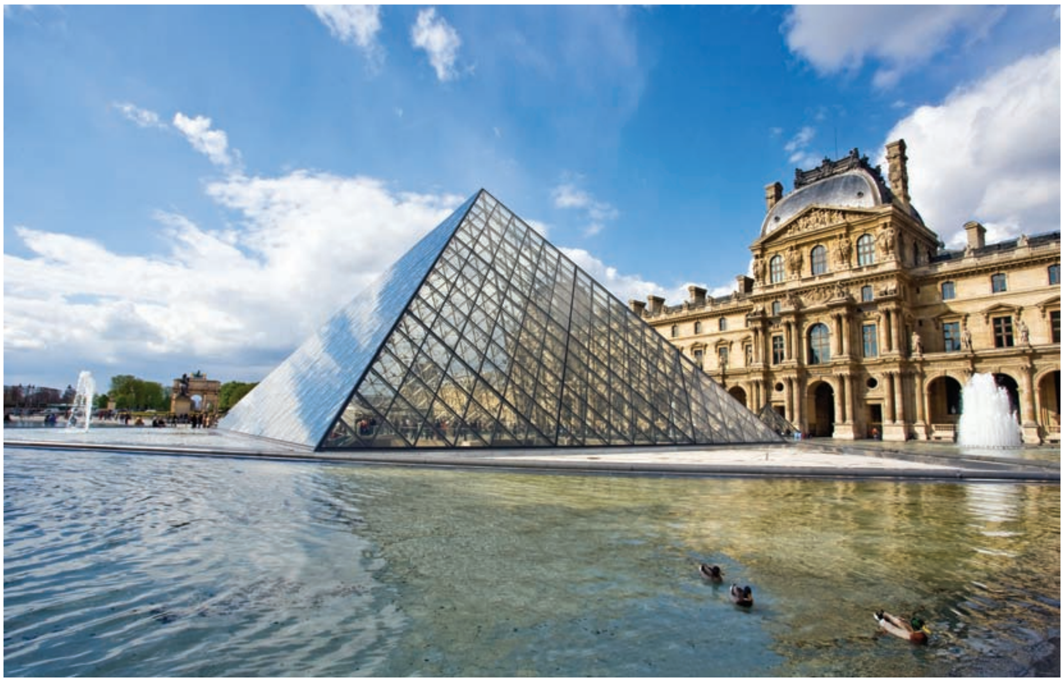


FIGURE 30.3 A large glass pyramid admits light into an underground addition to the Louvre museum, Paris, France. Architect: I. M. Pei and Partners. (Photo by Peter Barritt/Alamy Stock Photo)

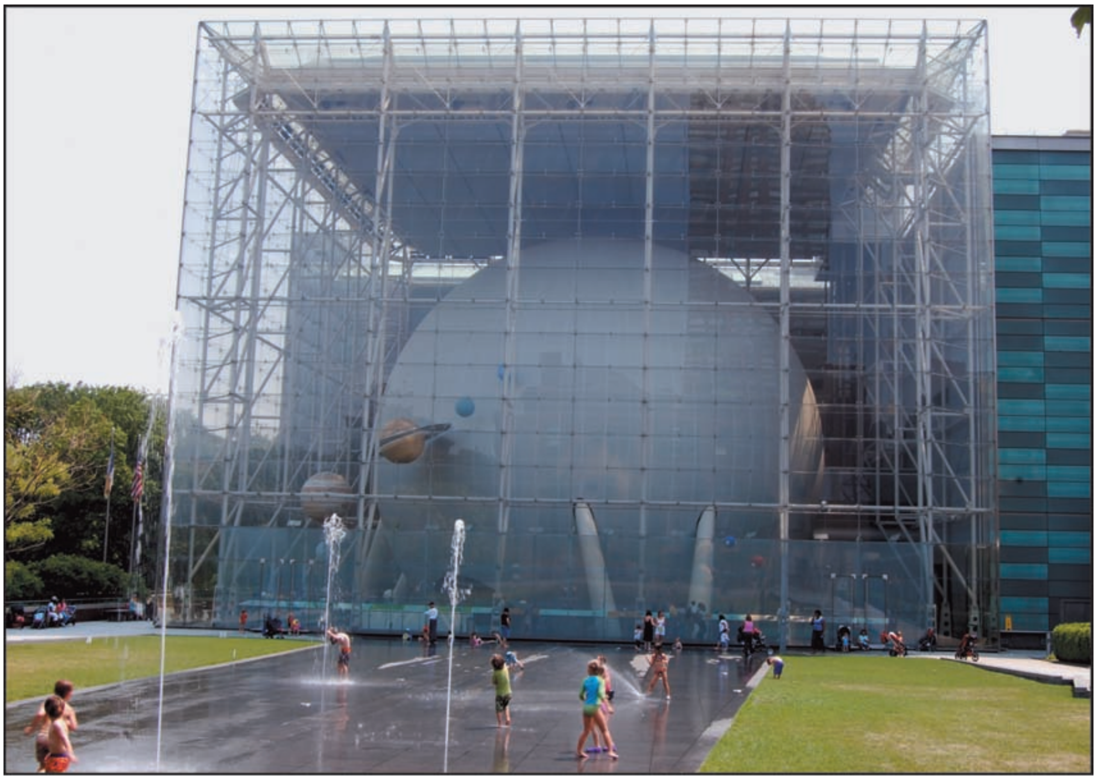


FIGURE 30.4 A transparent cube of glass, supported by a light steel structural backup, encloses the Rose Center for Earth and Space, New York City (see also Chapter 32, Figure 32.17). Architects: Polshek Partnership.

EXPAND YOUR KNOWLEDGE

Why Glass Is Transparent

Although glass is a solid substance, its molecular structure resembles that of a liquid. A typical solid is composed of numerous tiny crystals. Each crystal has a definite geometric form at the atomic level, which reflects the arrangement of its constituent atoms. The crystals are packed together in a regular manner to form a repeating network or lattice.

Crystals are formed when the material changes from its molten state to a solid state. Crystallization occurs abruptly at a specific temperature for a given material, called the *freezing point* (or the *crystallization temperature*). In the molten (liquid) state, a material has an amorphous (noncrystalline) structure. An amorphous structure is one in which the constituent atoms are joined to one another but not in a regular three-dimensional pattern—rather in a random pattern.

Glass is a material that has never crystallized. It becomes hard while still retaining its liquid structure. Thus, glass is sometimes called an *amorphous solid* or a *supercooled liquid*. Because of its amorphous structure, glass does not have a definite melting point like a crystalline solid.

(*Continued*)

The amorphous structure of glass is responsible for its transparency. All solids except glass and clear plastics are opaque to light. The opaqueness of a crystalline solid is explained by the fact that light is reflected at each crystal boundary as it passes through the solid. At each reflection, some light is lost.

Because there are numerous such crystal boundaries, even within a small thickness of a solid material, light goes through a large number of reflections, losing some light at each reflection. This makes the material behave as an opaque material. Glass is virtually one large crystal containing no internal boundaries, and that is why it is transparent. Several crystalline impurities, however, can make glass translucent or opaque.

The amorphous structure of glass is not merely a property of the materials of which the glass is made because many other materials can also be made to produce an amorphous structure on solidification. The amorphous structure of a solid material is also a property of the rate at which molten ingredients are cooled. If cooled slowly, the atoms in the molten mass have sufficient time to organize into a regular pattern to become a crystalline solid.

Therefore, in the manufacturing of glass, the molten ingredients must be cooled rapidly to below the crystallization temperature to prevent crystallization.

30.1 MANUFACTURE OF FLAT GLASS

The primary raw material for making *flat glass* (i.e., window glass, to distinguish it from glass block and other glass products) is sand. Chemically, sand is silicon dioxide, also called *silica*. Sand used for glass manufacturing is obtained from sandstone deposits. (Seashore sand is unsuitable for glassmaking because it has too many impurities.)

Although silica is all that is needed to make glass, other ingredients are added to modify several of its properties. The two major ingredients added to silica for making flat glass are sodium oxide and calcium oxide (lime). That is why flat glass is sometimes referred to as *soda-lime glass*. Soda-lime glass consists of approximately 72% silica, 15% sodium oxide, 9% calcium oxide, and 4% other minor ingredients.

One of the minor impurities in the ingredients for making glass is iron oxide, which occurs naturally in sand. Iron oxide gives a clear glass sheet its bluish-green tinge when viewed from its edge.

Sodium oxide works as a *flux*. A flux is an additive that lowers the melting point of the main ingredient—in this case, silica. The melting point of pure silica is very high—nearly 3,100°F (1,720°C). When sodium oxide is added to silica, the mixture melts at a much lower temperature, which reduces the cost of glassmaking.

Pure silica in its molten form is highly unworkable. It is so viscous and tacky that any bubbles of air or gas produced during melting do not readily escape from the molten mass. Sodium oxide also makes the molten mixture less viscous and, hence, more workable.

The mixture of silica and sodium oxide yields glass that is not too durable. It slowly dissolves in water and has low resistance to chemical attack. The addition of calcium oxide stabilizes the mix, resulting in a glass that is durable and more easily worked.

NOTE

Silica Glass

Glass made only from silica (silicon dioxide), with no other additives, is used in situations where its greater resistance to heat and higher transmissivity to radiation are required, such as in mercury vapor lamps and telescope mirrors. Glass made with pure silica is called *silica glass*.

The Float-Glass Process

Although the raw materials for making flat glass have remained virtually unchanged, the manufacturing process has evolved considerably over the years. In the process that is commonly used today, the raw materials are granulated, mixed together, and loaded into a furnace, where they melt.

Broken pieces of glass from an earlier batch and scrap glass are also loaded into the furnace at this stage. From the furnace, the molten material goes to a molten glass tank and then to a bed of molten tin. Because the density of molten tin is higher than that of molten glass, the latter floats on the molten tin bed.

The process is controlled so that a predetermined thickness of molten glass travels continuously over the tank of molten tin, called the *float bath*, Figure 30.5. As the molten glass moves to the end of the float tank, it is cooled rapidly to prevent crystallization. There, it solidifies into a sheet and then travels over rollers to the annealing chamber, called the *annealing lehr*.

The glass that enters the annealing lehr has internal stresses locked within its body. This is due to the thermal gradient that is set up between the external surfaces and the interior of the glass due to rapid cooling in the float bath.

In the annealing lehr, the glass is first heated sufficiently to relieve any stresses created during the solidifying process. It is then cooled very slowly so that every glass particle cools at the same rate to ensure that no stresses are frozen in the glass. The annealing lehr is, therefore, several hundred feet long.

NOTE

Invention of the Float-Glass Process

The float-glass process was first used in 1959 by Pilkington Brothers Limited near Liverpool, England, and has since become a worldwide standard for the manufacturing of glass.

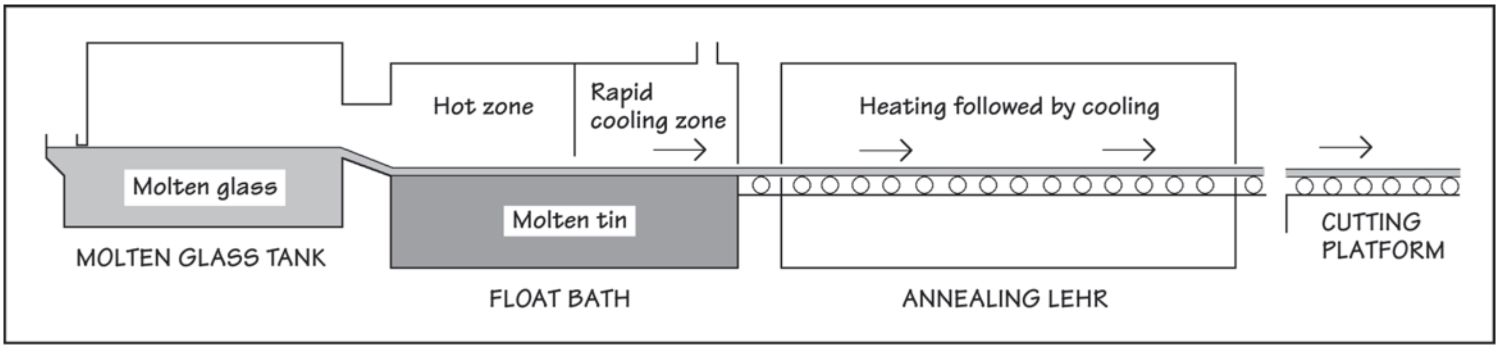

Hot zone
Rapid cooling zone
Heating followed by cooling
Molten glass
Molten tin
MOLTEN GLASS TANK
FLOAT BATH
ANNEALING LEHR
CUTTING PLATFORM

FIGURE 30.5 Outline of the float-glass manufacturing process.

At the end of the annealing lehr, the glass sheet emerges as a continuous ribbon at room temperature, free of any internal stresses, Figure 30.6. It is then cut into desired lengths by automatic cutters, packed, and transported to its destination, Figure 30.7.

Because the top surface of a liquid must be uniformly horizontal due to gravity, the floating of molten glass over molten tin ensures that the top and bottom surfaces of glass are parallel. This provides a glass sheet of uniform thickness—an important requirement to ensure distortion-free vision through glass.

The glass obtained from this process is called *float glass* to distinguish it from sheet glass and plate glass, which were the two types of flat glass used before the discovery of the float-glass manufacturing process. Virtually all flat glass manufactured today is produced by the float-glass process. Sheet glass and plate glass are no longer commercially produced.

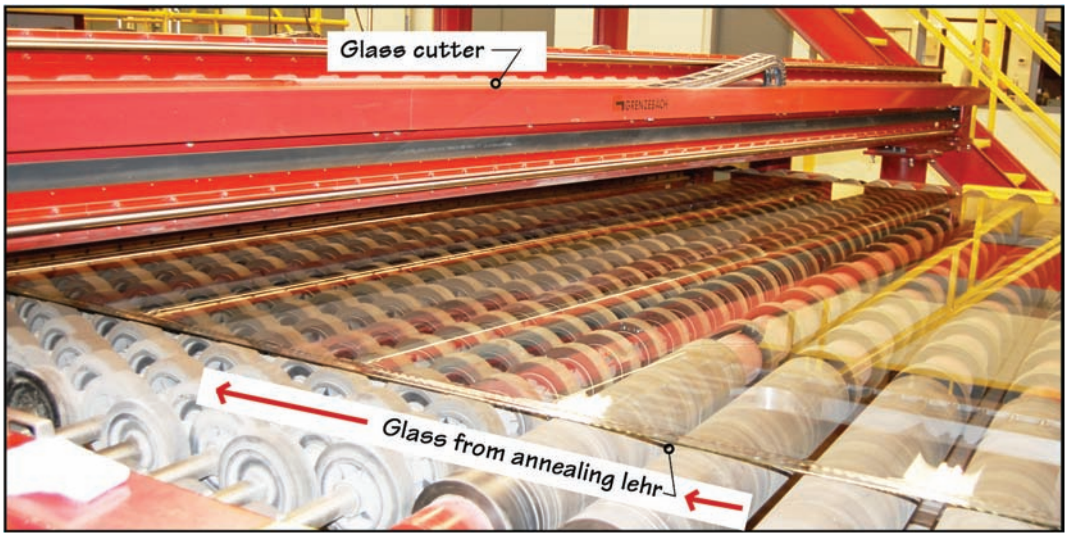

Glass cutter
Glass from annealing lehr

FIGURE 30.6 Traveling on rollers, the glass, in float-glass manufacturing process, emerges as an endless ribbon from the annealing lehr before reaching the cutting machine.

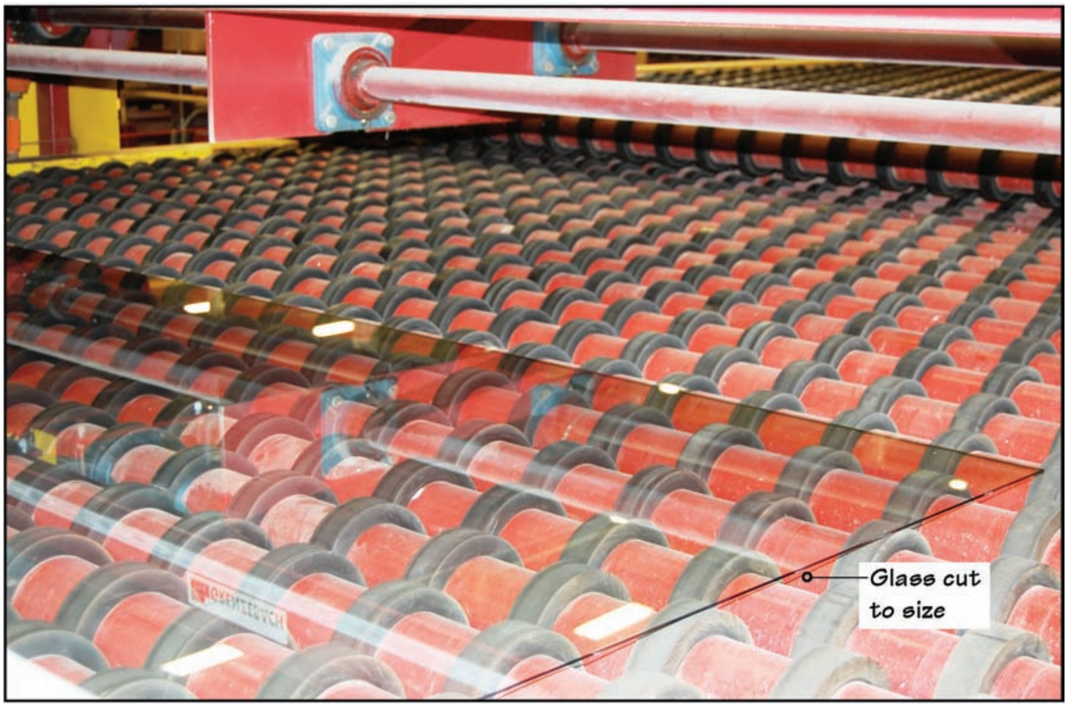

Glass cut to size

FIGURE 30.7 Glass is cut by automatic cutters to the required sizes before packing and shipping.

TYPICAL FLAT GLASS THICKNESS

The commonly used nominal thicknesses of flat glass range from $\frac{3}{32}$ in. to 1 in. Glass of $\frac{3}{32}$-in. thickness is referred to as *single-strength* (SS) *glass*, and that of $\frac{1}{8}$-in. thickness is called *double-strength* (DS) *glass*. Manufacturers must be consulted for the availability of certain thicknesses before specifying it for a project.

NOTE

Nominal versus Actual Thickness of Flat Glass

Glass thickness is given in terms of its nominal thickness. The actual glass thickness is its nominal thickness plus or minus a tolerance. For example, the actual thickness of a $\frac{1}{4}$-in. (6-mm)-thick glass sheet must lie between 0.219 in. (5.56 mm) and 0.244 in. (6.20 mm).

30.2 TYPES OF HEAT-MODIFIED GLASS

Flat glass obtained from the float-glass process, without any further treatment, is the basic glass, referred to as *annealed glass*. Annealed glass, which may be clear or tinted, is the most commonly used glass type in buildings. However, where a stronger glass is required, annealed glass is heat treated before use. Heat treatment increases the bending strength and the temperature resistance of glass and makes it more suitable for applications where annealed glass is inadequate. There are three types of heat-modified glass:

- Tempered glass, also referred to as *fully tempered* (FT) *glass*
- Heat-soaked tempered glass
- Heat-strengthened (HS) glass

NOTE

Annealed, Tempered, Heat-Soaked, and Heat-Strengthened Glasses

Annealed glass is the basic glass, obtained directly from the float-glass process. *Tempered glass, heat-soaked glass,* and *heat-strengthened glass* are obtained by heat treating annealed glass.

TEMPERED GLASS

Tempering is the exact opposite of annealing. Whereas annealing (the process of slow cooling after heating) reduces or eliminates locked-in stresses, tempering produces them. Tempering involves heating the glass below its softening point, to approximately 1,300°F (700°C), and suddenly cooling (quenching) it by blowing a jet of cold air on all surfaces of the glass simultaneously. This causes the outer layers of the glass to harden quickly while the interior of the glass is still soft. As the interior begins to cool, it tends to shrink but is prevented from doing so by the already-hardened outer glass surfaces, Figure 30.8. Consequently, the exterior of the glass comes under a state of compression and the interior under a state of compensating tension.

Like all brittle materials, glass is weak in tension. Therefore, a glass sheet is weak in bending also, because bending creates tensile (and compressive) stresses in the sheet. The locked-in compressive stresses in the outer layers of tempered glass cancel (or reduce) the tensile stresses produced by bending. Consequently, tempered glass is approximately four times stronger than annealed glass in bending. It can also withstand greater deflection than annealed glass of the same thickness, Figure 30.9, and is far more resistant to impact and thermal stresses.

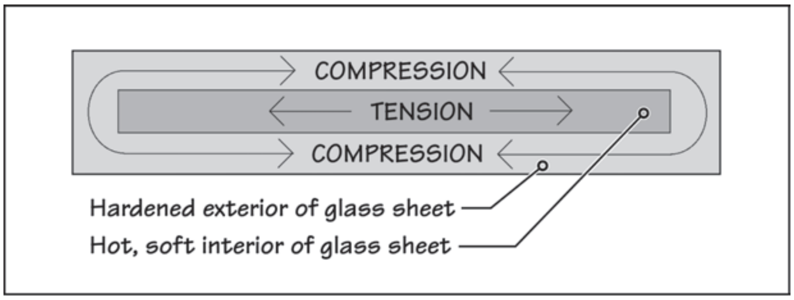

COMPRESSION
TENSION
COMPRESSION
Hardened exterior of glass sheet
Hot, soft interior of glass sheet

FIGURE 30.8 When the heated glass is quenched with cold air during the tempering process, the outside layers of glass become hard while the interior remains hot and soft. As the interior of the glass cools, it shrinks and tends to pull the hardened outside layers inward, producing compressive stresses in them. Because the outside layers have already hardened, they resist the inward pull. Consequently, the interior of the glass comes under tension. These stresses are permanently locked in a tempered glass sheet.

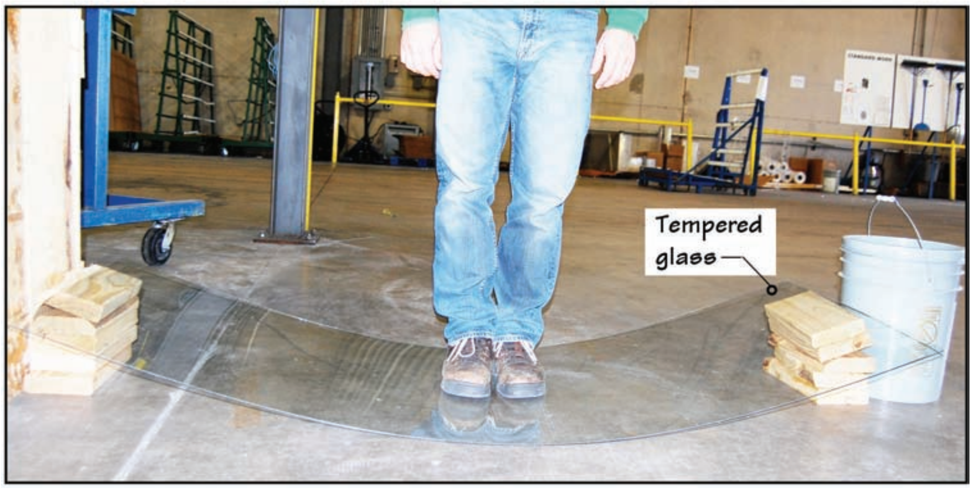


FIGURE 30.9 A makeshift demonstration of the ductility of tempered glass set up in a glass tempering facility in which a 6-ft-long sheet of glass is supported at each end by a stack of five 2-by lumber members and loaded with the weight of an adult person. Observe the ability of tempered glass to deform (deflect) substantially under load.

Tempering does not affect other properties of glass, such as solar heat gain, U-value, or the color of glass. However, because of the bowing and warping caused by the shrinkage of glass during heat treatment, tempered glass may contain a slightly noticeable distortion of view under some light conditions, which is generally not objectionable.

Tempering must be done after the glass has been cut to size. A tempered glass sheet must not be cut, drilled, or edged because these processes release the locked-in stresses, causing the glass to disintegrate abruptly. Abrasive blasting and etching may be done with some care. However, both abrasive blasting and etching reduce the thickness of the outer compressed layers, reducing the effectiveness of tempering.

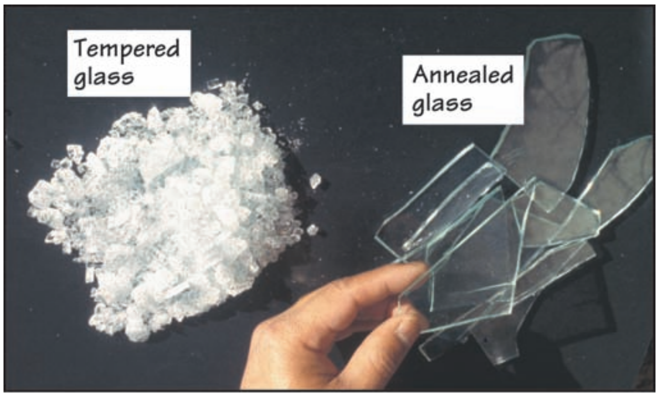


FIGURE 30.10 Breakage patterns of tempered glass and annealed glass. Tempered glass breaks into tiny square-edged granules. Annealed glass breaks into large, sharp-ended pieces.

USE OF TEMPERED GLASS

When tempered glass breaks, it breaks into tiny square-edged, cubicle-shaped granules—a breakage pattern usually referred to as *dicing*, Figure 30.10. Annealed glass, on the other hand, breaks into long, sharp-edged pieces. Tempered glass is, therefore, used in hazardous locations, provided that it meets the requirements of safety glazing, as described in Section 30.9.

SPONTANEOUS BREAKAGE OF TEMPERED GLASS

Nickel sulfide and certain other impurities present in glass ingredients do not fully melt during glass manufacturing. They are known to expand after days or even years of glass manufacturing when subjected to extreme thermal stresses or thermal shock (e.g., sudden cooling of sun-heated glass by rainwater). When this expansion occurs in tempered glass, it creates excessive tensile stress in the glass, resulting in its spontaneous breakage.

This breakage, although rare, occurs abruptly and can be a safety hazard. Building codes require that if there is a walking or other usable surface under a tempered glass opening, a protective screen must be provided below it to prevent injuries to humans.

HEAT-SOAKED TEMPERED GLASS

When it is necessary to reduce or eliminate spontaneous breakage of tempered glass, heat-soaked tempered glass is used. In the heat-soaking process, tempered glass panes are subjected to cyclical heating and cooling to simulate long-term field conditions. Glass that does not break in the process is safe against spontaneous breakage and is called *heat-soaked tempered glass*.

Because the testing is expensive and results in the destruction of a certain percentage of tempered glass panes, heat-soaked glass is expensive and is used only in projects where its higher cost can be justified.

HEAT-STRENGTHENED GLASS

Heat-strengthened glass falls in between annealed glass and tempered glass. It is heat treated in exactly the same way as tempered glass, but during quenching, a much smaller volume of air is used so that the glass cools more slowly. It is nearly twice as strong as annealed glass in bending.

Heat-strengthened glass breaks into pieces that are sharper than those of tempered glass but more blunt than those obtained from the breakage of annealed glass. In other words, heat-strengthened glass does not "dice" on breaking. Therefore, heat-strengthened glass is not a safety glass. Like tempered glass, heat-strengthened glass cannot be cut or drilled after heat treatment.

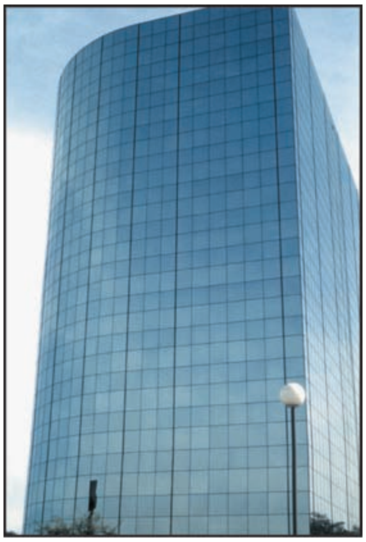


FIGURE 30.11 An example of a typical all-glass curtain wall building.

USE OF HEAT-STRENGTHENED GLASS

The primary use of heat-strengthened glass is in situations where the glass is subjected to large thermal stresses. One such situation is the spandrel area of an all-glass curtain wall, Figure 30.11. A spandrel area is an area of a wall that is between the head of a window on

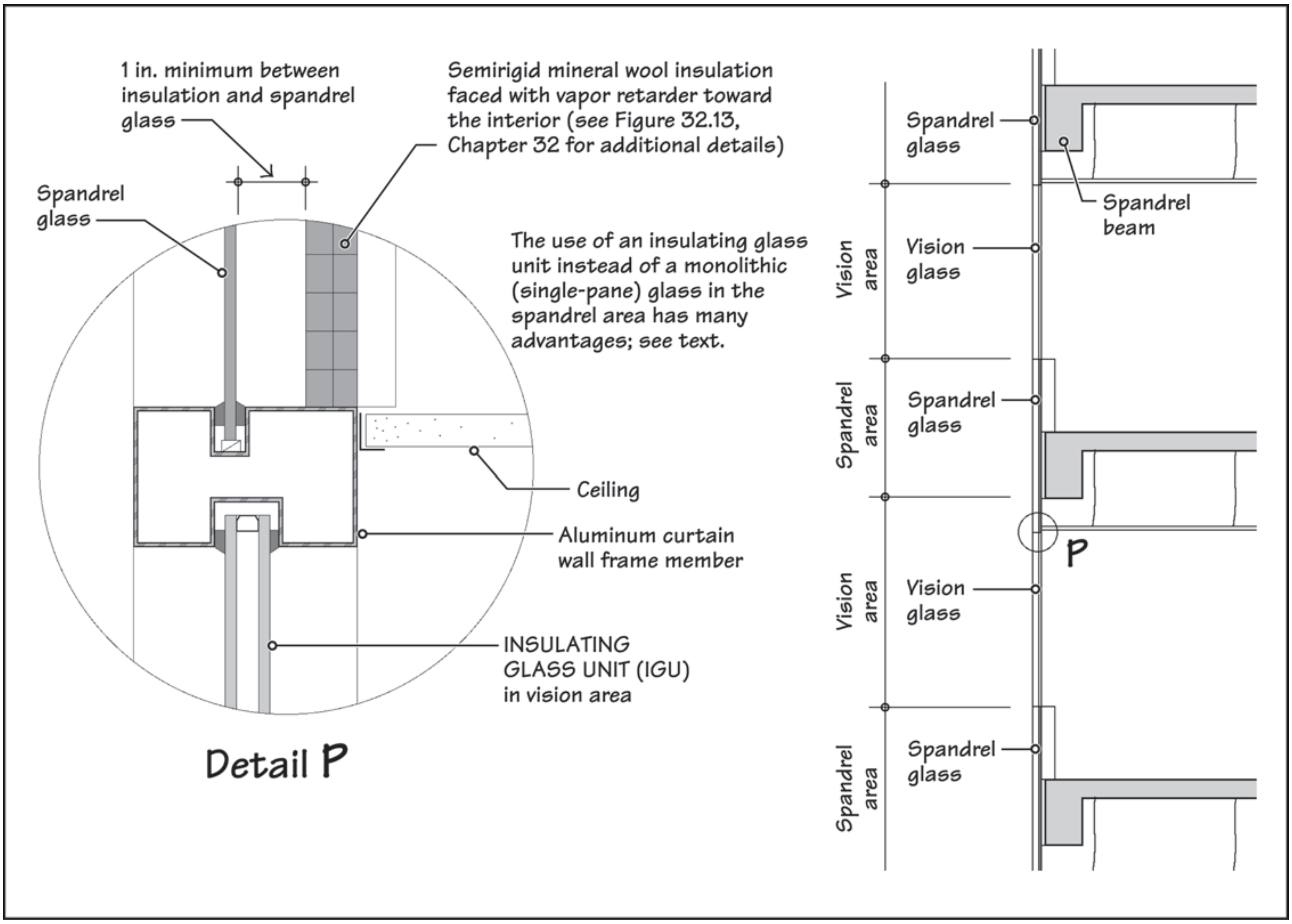

1 in. minimum between insulation and spandrel glass
Semirigid mineral wool insulation faced with vapor retarder toward the interior (see Figure 32.13, Chapter 32 for additional details)
Spandrel glass
The use of an insulating glass unit instead of a monolithic (single-pane) glass in the spandrel area has many advantages; see text.
Ceiling
Aluminum curtain wall frame member
INSULATING GLASS UNIT (IGU) in vision area
Detail P
Spandrel glass
Spandrel beam
Vision area
Vision glass
Spandrel area
Spandrel glass
P
Vision area
Vision glass
Spandrel area
Spandrel glass

FIGURE 30.12 A section through an all-glass curtain wall showing spandrel glass and vision glass areas (see also Chapter 7, Figure 7.29). Although monolithic glass has been shown in the spandrel area (Detail P), the same insulating glass unit used in the vision area may be used in the spandrel area.

NOTE

Ceramic Frit on Glass

A ceramic frit coating is deposited on glass in individual dots or lines and then fused (baked) into the glass under high temperature. The coating can be of different colors and can be opaque or translucent. Fritted glass can use any pattern to produce images or graphic designs on glass.

one floor and the sill of the window on the floor above. This is the part of the building facade that includes edge beams and the floor slab. The purpose of spandrel glass panes is to hide the structural components behind them. Thus, an all-glass curtain wall consists of two distinct areas of glass: vision glass and spandrel glass, Figure 30.12.

In colder regions of North America, it is common practice to use monolithic (single) sheets of glass in spandrel areas and insulating glass units in vision areas. (Refer to Section 30.6 for the description of an insulating glass unit.) To prevent see-through, the spandrel glass is opacified either with a ceramic frit coating or a polyester film.

To improve the energy performance of the glass curtain wall, spandrel areas are generally insulated. At least a 1-in. space is generally recommended between the insulation and the glass to simulate the depth of view of vision glass. Using the same type of glass in both the vision and spandrel areas of the wall (particularly a tinted-reflective glass) adds to the blend between the vision and the spandrel panels.

Because of the presence of insulation, the spandrel glass in an all-glass curtain wall does not dissipate the Sun's heat as readily as the vision glass. Consequently, the spandrel glass is subjected to much greater thermal stress than the vision glass. Because of its greater strength compared to annealed glass, heat-strengthened glass is usually specified for the spandrel panels.

The space between the insulation and spandrel glass is particularly susceptible to condensation, which may lead to wetting of insulation and corrosion of metals. Therefore, the entry of water vapor into this space should be prevented through the use of a good vapor retarder that is fully sealed toward the interior (see Chapter 32 for additional details). Condensation effects can be reduced by the use of insulating glass units in spandrel areas.

The use of insulating glass units in spandrel areas in place of monolithic glass is fairly common in milder climates of North America, which gives a better blend between vision and spandrel areas and may preclude the use of spandrel insulation. The inward glass pane of such an insulating glass unit in the spandrel is opacified and heat strengthened. In situations where a glass pane is subjected to uneven solar shading, the vision areas may also require the use of a heat-strengthened glass.

HEAT-STRENGTHENED GLASS VERSUS TEMPERED GLASS

Although tempered glass is nearly twice as strong as heat-strengthened glass, heat-strengthened glass is preferred over tempered glass in most situations, except those that mandate the use of tempered glass (e.g., as safety glazing). The reasons are as follows:

- Spontaneous breakage is less of a problem in heat-strengthened glass.
- When heat-strengthened glass breaks, most of it stays within the opening, similar to annealed glass. Tempered glass, on the other hand, fractures in small pieces and tends to evacuate the opening.
- There is generally less optical distortion in heat-strengthened glass.

BENT GLASS

Bent glass is made from float glass that has been heated sufficiently to become plastic so that it can be bent to shape. Various forms of bent-glass shapes have been used in windows and skylights. Bent tempered glass is also available and is commonly used in revolving doors, curved glass handrails, elevator cars, and office partitions.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The microscopic (atomic) structure of glass resembles that of
   a. solids.
   b. liquids.
   c. gases.
   d. none of the above.

2. To make glass transparent, the molten glass ingredients must be
   a. cooled very slowly during manufacture.
   b. cooled slowly during manufacture.
   c. cooled rapidly during manufacture.
   d. any one of the above.

3. The glass obtained from the float-glass process without any further treatment is called
   a. sheet glass.
   b. annealed glass.
   c. tempered glass.
   d. heat-strengthened glass.
   e. plate glass.

4. If glass is $\frac{1}{8}$ in. (3 mm) thick, it is also called
   a. single-layer glass.
   b. single-strength glass.
   c. double-strength glass.
   d. basic glass.
   e. monolithic glass.

5. Which of the following types of glass is generally used as safety glass?
   a. Sheet glass
   b. Annealed glass
   c. Tempered glass
   d. Heat-strengthened glass
   e. Plate glass

6. Which glass type is commonly specified for the spandrel areas of an all-glass curtain wall?
   a. Sheet glass
   b. Annealed glass
   c. Tempered glass
   d. Heat-strengthened glass
   e. Plate glass

7. Which of the following glass types has locked-in stresses?
   a. Tempered glass
   b. Heat-soaked tempered glass
   c. Heat-strengthened glass
   d. All of the above
   e. None of the above

8. To obtain heat-soaked tempered glass, the glass must be tempered first and then
   a. annealed.
   b. etched.
   c. heat strengthened in a furnace.
   d. subjected to cyclic heating and cooling.
   e. all of the above.

9. Which of the following glass types, when broken, breaks into tiny square-edged granules?
   a. Tempered glass
   b. Heat-strengthened glass
   c. Annealed glass
   d. None of the above

10. Spontaneous breakage generally occurs in
   a. annealed glass.
   b. heat-strengthened glass.
   c. heat-soaked tempered glass.
   d. tempered glass.
   e. laminated glass.

30.3 GLASS AND SOLAR RADIATION

When solar radiation (i.e., direct solar beam) falls on a glass surface, part of it is transmitted through glass, part is reflected, and part is absorbed by the glass. A $\frac{1}{8}$-in.-thick clear glass sheet transmits approximately 85%, reflects 10%, and absorbs nearly 5% of solar radiation. In other words, the transmissivity, reflectivity, and absorptivity of clear glass for solar radiation are 0.85, 0.10, and 0.05, respectively. Thus, if 100 units of solar energy fall on a clear glass sheet, 85 units are transmitted to the interior, 10 units are reflected to the exterior, and 5 units are absorbed by the sheet, Figure 30.13.

The 5 units of solar radiation absorbed by a clear glass sheet increase its temperature, and the glass becomes a low-temperature (long-wave) radiator. It releases (by radiation and convection) R_i units of absorbed heat to the inside and R_o units to the outside, so that $R_i + R_o = 5$ units.

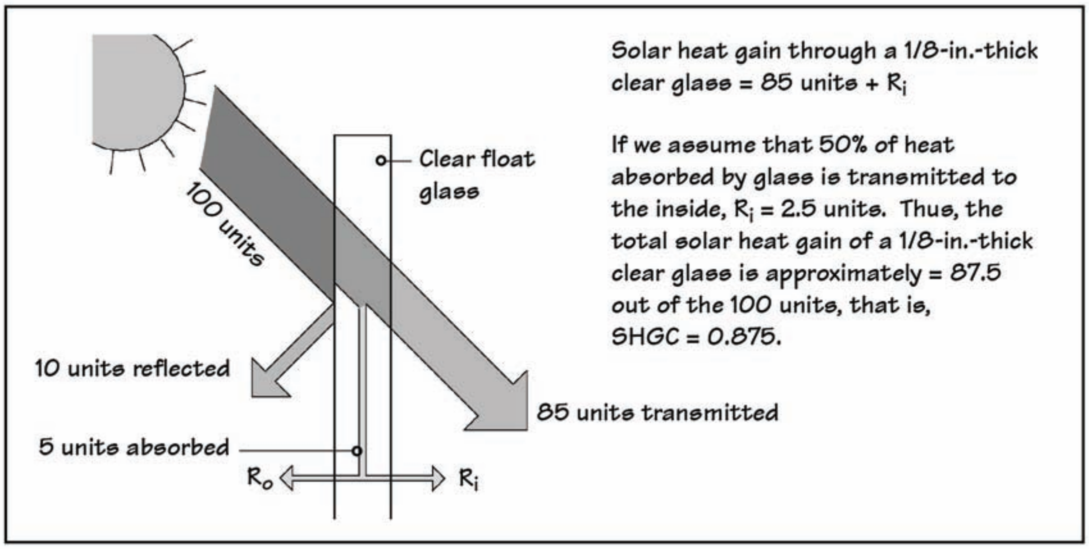

Solar heat gain through a 1/8-in.-thick clear glass = 85 units + R_i
If we assume that 50% of heat absorbed by glass is transmitted to the inside, R_i = 2.5 units. Thus, the total solar heat gain of a 1/8-in.-thick clear glass is approximately = 87.5 out of the 100 units, that is, SHGC = 0.875.
Clear float glass
100 units
10 units reflected
85 units transmitted
5 units absorbed
R_o
R_i

FIGURE 30.13 Properties of a $\frac{1}{8}$-in.-thick clear glass with respect to solar radiation.

NOTE

SHGC Value and the Energy Code

The International Energy Conservation Code (IECC) places restrictions on the SHGC values of glass used in building fenestration. For example, in a commercial building, the maximum SHGC value of glass used in windows is limited to 0.25 for climate zones 1 to 3 (warmer climates). The value of 0.25 (in the 2015 edition of the IECC) represents a reduction of 37.5% from 0.4 (in the 2006 edition of the IECC), highlighting the importance of SHGC in affecting energy use (and, hence, sustainability) in warm climates.

The 2015 IECC allows an increase in the maximum SHGC values for cooler climates. For example, the maximum value of SHGC for climate zones 4 to 6 is 0.4 and for climate zones 7 and 8, it is 0.45.

Note that this information applies to compliance with the prescriptive provisions of the IECC. If the whole-building energy modeling approach is used, the prescriptive requirements need not be followed.

The relative values of R_i and R_o depend on the internal and external air temperatures. A greater amount of heat is released toward the cooler side. Thus, if the inside air is cooler than the outside air, $R_i > R_o$ (e.g., R_i may equal 3.0 units, so $R_o = 2.0$ units). Conversely, if the outside air is cooler than the inside air, $R_o > R_i$.

When inside and outside air temperatures are the same, $R_i = R_o = 2.5$ units. In such a case, the total amount of solar radiation penetrating the glass will equal $85 + 2.5 = 87.5$ units. In other words, 87.5% of solar radiation incident on the glass penetrates the glass.

SOLAR HEAT-GAIN COEFFICIENT (SHGC)

A commonly used measure of how well a glass sheet performs with respect to direct solar radiation is the *solar heat-gain coefficient* (SHGC). It is defined as the amount of solar radiation that penetrates a given glass (including the absorbed radiation that is subsequently released to the interior) divided by the solar radiation incident on the glass:

$$\text{SHGC} = \frac{\text{solar energy gain through a glass}}{\text{solar energy incident on glass}}$$

Thus, as shown in Figure 30.13, SHGC $= 0.875$ for a $\frac{1}{8}$-in.-thick clear glass. The smaller the value of SHGC, the smaller the heat gain through the building. For warm (southern) regions of the United States, SHGC should be as low as possible. For cold (northern) regions of the United States, a higher SHGC value is desirable because it may provide daytime heating of the building through glazed openings.

SHADING COEFFICIENT (SC)

Another measure closely related to SHGC is the *shading coefficient* (SC). SC is defined as the solar heat gain through a given glass divided by the solar heat gain through an unshaded, clear $\frac{1}{8}$-in.-thick glass under the same internal and external conditions. In other words, the SC of glass is a ratio of the SHGC of glass and the SHGC of $\frac{1}{8}$-in.-thick clear glass:

$$\text{SC} = \frac{\text{SHGC of glass in question}}{\text{SHGC of } \frac{1}{8}\text{-in.-thick clear glass}}$$

From the preceding definition, the SC of a $\frac{1}{8}$-in.-thick clear glass is 1.0. This is practically the maximum possible value of the shading coefficient. The shading coefficient of a clear $\frac{3}{32}$-in.-thick glass is nearly 1.01.

VISIBLE TRANSMITTANCE (VT) AND THE LIGHT-TO-SOLAR GAIN (LSG) INDEX

Because transparency is the primary reason for using glass in buildings, another important property of glass is its ability to transmit light (the visible part of solar radiation; see the first Principles in Practice section at the end of this chapter). *Visible transmittance* (VT) is defined as the percentage of the visible part of solar radiation transmitted through glass. For $\frac{1}{8}$-in.-thick clear glass, VT is approximately 0.90.

The LSG (light-to-solar gain) index of a glass is the ratio of VT and SHGC:

$$\text{LSG index} = \frac{\text{VT of glass}}{\text{SHGC of glass}}$$

The greater the value of the LSG index, the more efficient the glass is with respect to reducing the solar heat gain and increasing light transmission. Because VT and SHGC for a $\frac{1}{8}$-in.-thick clear glass are 0.90 and 0.875, respectively, the LSG index for this glass is $0.90/0.875 = 1.03$. Glass manufacturers can provide glass with a high LSG index by using a spectrally selective, low-E coating on glass (see Section 30.5).

ULTRAVIOLET TRANSMITTANCE (UVT)

Radiation, in general, has an adverse effect on human skin and eyes. It is also responsible for fading the colors of fabrics, carpets, and artwork. Ultraviolet radiation has a higher energy content than radiation at longer wavelengths. Thus, although it is only 3% of the total solar radiation, the material degradation potential of ultraviolet radiation is far greater than that of visible, or long-wave, radiation. Manufacturers of glass quote the ultraviolet transmittance (UVT) of their products. A glass with a lower UVT is generally preferable.

30.4 TYPES OF TINTED AND REFLECTIVE GLASS

Two commonly used glass products that are specially produced to lower solar heat gain are tinted glass and reflective glass. A glass may be tinted, reflective, or tinted and reflective. Tinted and reflective glass is commonly used in the curtain walls of an all-glass building to reduce unwanted heat gain through the building.

TINTED (OR HEAT-ABSORBING) GLASS

Glass can be tinted to a desired color by adding metallic pigments to the molten constituents of glass during its manufacture. Tinted glass is also called *heat-absorbing glass* because it absorbs more solar radiation than clear glass under identical conditions.

A thicker glass, made with exactly the same concentration of pigment and the same batch of molten constituents as a thinner glass, appears to be deeper in color because a greater amount of light is absorbed by a thicker glass. For the same reason, a thicker tinted glass absorbs more heat than a thinner tinted glass.

As a result of greater heat absorption, the temperature of tinted glass is higher than that of clear glass when direct solar radiation is incident on the glass. A thick tinted glass sheet exposed to intense solar heat should be heat strengthened to withstand greater thermal stresses.

The most commonly used colors in tinted glass are bronze, gray, and blue-green. If everything else is the same, a green-tinted glass has a higher LSG index (i.e., is more efficient in reducing the solar heat gain and increasing light transmission) than other tinted glass.

REFLECTIVE GLASS

Reflective glass works as a mirror from the outside during the day, hiding interior activity. At night, however, the interior activity is visible from the outside when the interior space is lit.

Reflective glass is made by bonding metal or metal oxide coatings to one surface of a clear or tinted glass. Some of the metals used are chrome, stainless steel, titanium, and copper oxide. The coating is extremely thin so that sufficient light can pass through the glass and is deposited on the glass by one of two methods:

- Magnetic sputtering
- Pyrolytic deposition

Magnetic sputtering requires a large vacuum chamber in which atoms of metal or metal oxide are dislodged from the original material by an induced electrical charge. These atoms impinge on the surface of the glass placed in the chamber, creating a thin layer of coating. If the glass is required to be tempered or heat strengthened, it is heat treated prior to the application of the sputtered coating.

In the pyrolytic deposition process, a metal or metal oxide coating is applied to hot glass. This is accomplished either in the heat-strengthening furnace (for a heat-treated glass), at the hot end of the annealing lehr, or at the cool end of the float bath for annealed glass. Thus, the reflective coating is virtually fused into the glass sheet because the glass constituents are in a semisolid state when the coating is applied. Consequently, a pyrolytically deposited coating is more durable than a magnetically sputtered coating.

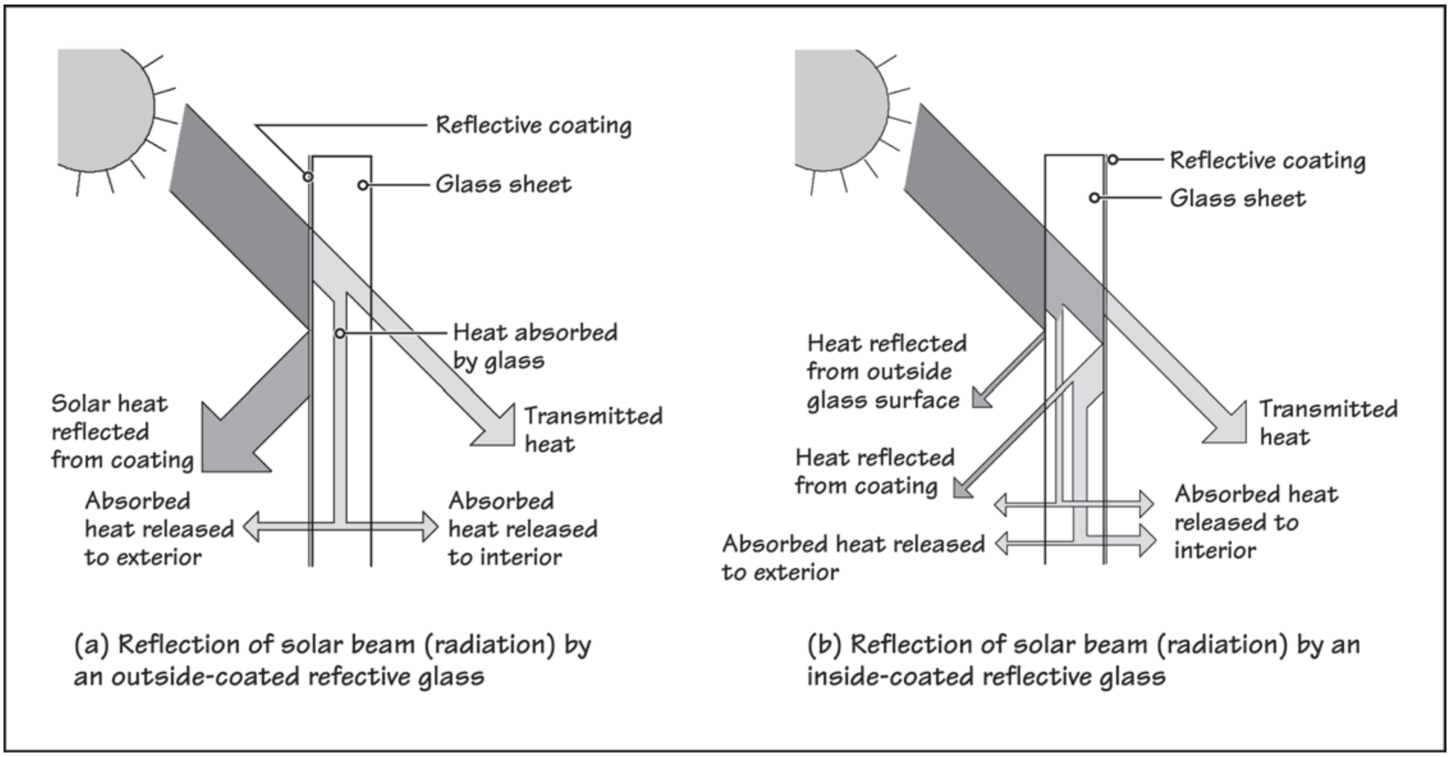

Reflective coating
Glass sheet
Heat absorbed by glass
Solar heat reflected from coating
Transmitted heat
Absorbed heat released to exterior
Absorbed heat released to interior
(a) Reflection of solar beam (radiation) by an outside-coated refective glass
Reflective coating
Glass sheet
Heat reflected from outside glass surface
Heat reflected from coating
Transmitted heat
Absorbed heat released to interior
Absorbed heat released to exterior
(b) Reflection of solar beam (radiation) by an inside-coated reflective glass

FIGURE 30.14 An outside-coated reflective glass reflects a greater amount of solar radiation than an inside-coated reflective glass but is less durable.

REFLECTIVE GLASS AND SOLAR RADIATION

A reflective coating on the outside surface of a glass is more effective in reflecting solar radiation compared with the coating on the inside surface, Figure 30.14. This is due to the fact that in an inside-coated glass, the solar radiation passes through the glass twice, and hence it goes through two absorption cycles instead of one (in an outside-coated glass). Thus, an inside-coated glass will become warmer (and be subjected to greater thermal stress) than an outside-coated glass under the same conditions and will generally require heat strengthening. This is particularly true if the glass is also tinted.

The durability of the coating in an outside-coated glass must be examined. A sputtered coating is too soft to withstand the abrasive effects of wind and rain. Therefore, a sputtered coating should be exposed only to the interior. A more protected location, such as surface 2 or surface 3 of an insulating glass unit, is preferred for sputtered coating (see Section 30.6 for the description of an insulating glass unit). A pyrolytic coating may be exposed to the exterior, but the cleaning of such a glass must be done per the manufacturer's recommendations.

Reflective glass reduces solar heat gain but also reduces visible transmittance (VT). Because lower VT is generally undesirable, the use of reflective glass has decreased since the introduction of new spectrally selective, low-E coatings for glass, which provide low solar heat gain without greatly reducing VT (see Section 30.5).

Another disadvantage of reflective glass is that it reflects the solar radiation toward the street and the surrounding buildings. The glare created by such reflection is known to have temporarily blinded passing motorists. Several high-rise, all-glass buildings located on the opposite sides of a narrow street with reflective glass facades may make a street (particularly a narrow street) unduly warm in the summer due to multiple reflections of solar radiation, Figure 30.15 .

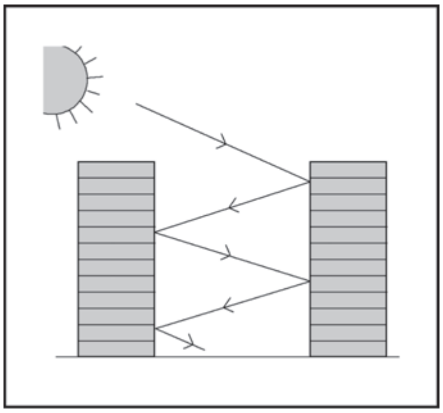


FIGURE 30.15 The use of reflective glass on the opposite facades of all-glass high-rise buildings can make a narrow street become unduly warm, particularly during summertime.

30.5 GLASS AND LONG-WAVE RADIATION

The properties of glass (SHGC, VT, and UVT) discussed previously are relevant only with respect to solar radiation (see the first Principles in Practice section at the end of the chapter). The properties of glass with respect to long-wave radiation are shown diagrammatically in Figure 30.16. Of the 100 units of long-wave radiation incident on glass, 90 units are absorbed, 10 units are reflected, and practically nothing is transmitted through glass. In other words, the long-wave absorptivity of glass is 0.90, reflectivity is 0.10, and transmissivity is zero. Because absorptivity is equal to emissivity (see Section 5.8), the emissivity of glass is also 0.90.

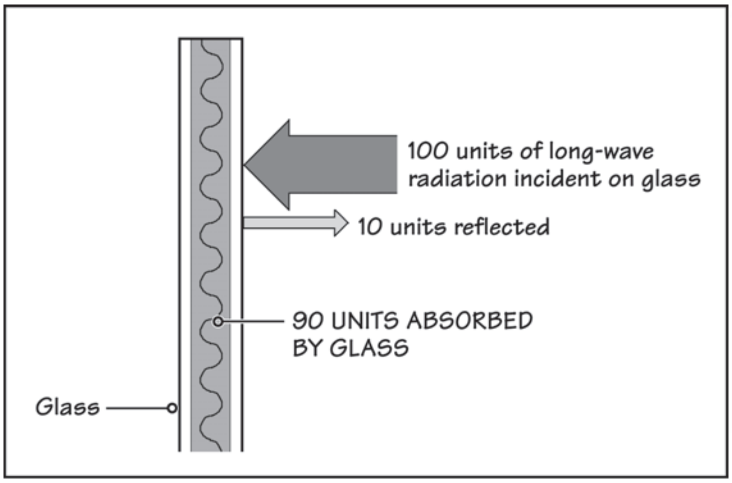

100 units of long-wave radiation incident on glass
10 units reflected
90 UNITS ABSORBED BY GLASS
Glass

FIGURE 30.16 Reflection, absorption, and transmission characteristics of glass with respect to long-wave radiation.

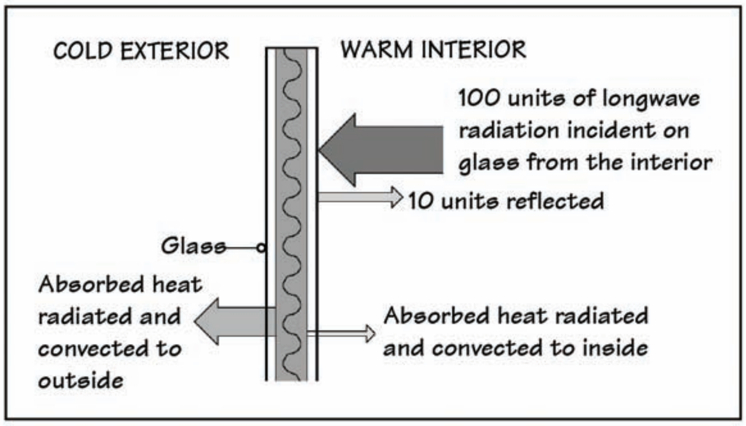

COLD EXTERIOR
WARM INTERIOR
100 units of longwave radiation incident on glass from the interior
10 units reflected
Glass
Absorbed heat radiated and convected to outside
Absorbed heat radiated and convected to inside

FIGURE 30.17 Long-wave radiation absorbed by (float) glass from a warm interior and its dissipation by radiation and convection to a cold exterior. Observe that the majority of interior heat is dissipated to the outside; very little returns to the interior.

Of the 90 units of long-wave radiation absorbed by glass, part is radiated and convected toward the interior and part toward the exterior. If the outside air temperature is low—a typical winter condition—most of the absorbed heat is released toward the outside. In other words, the glass is soaking up 90% of the radiant heat incident on it from the enclosure, most of which is being dissipated to the outside, Figure 30.17.

At this stage, it is important to appreciate that this mode of heat transfer is not the only mode by which heat from the inside is being lost to the outside. The other important mode of heat transfer is due to the temperature difference between the inside and outside air.

LOW-EMISSIVITY (LOW-E) GLASS

A simple way to reduce the loss of interior heat absorbed by glass to the exterior is to coat the surface of the glass with a low-emissivity (low-E) film. Because the emissivity of a surface is equal to its absorptivity, lowering the emissivity implies lowering its (long-wave) absorptivity and, hence, increasing the surface's (long-wave) reflectivity.

Consider once again 100 units of interior heat incident on a glass. If the interior surface of this glass is coated with a low-E coating with an emissivity of 0.1, 10% of the heat from the room interior will be absorbed and 90% will be reflected back to the interior, Figure 30.18. A glass with a low-emissivity coating is called a *low-E glass*.

Thus, low-E glass considerably reduces radiant heat loss through the glass and is extremely useful in cold climates. In other words, the behavior of low-E glass to long-wave radiation is similar to the behavior of reflective glass to solar radiation. Just as reflective glass reflects solar radiation back to the exterior, low-E glass reflects long-wave interior heat back to the interior. Low-E glass is also effective in warm climates, although less so (see the box entitled "Location of a Low-E Coating in an IGU" in Section 30.7).

A low-E coating is almost invisible to the eye because it transmits most of the visible solar radiation. A *spectrally selective low-E coating* is similar to a low-E coating in that it transmits most

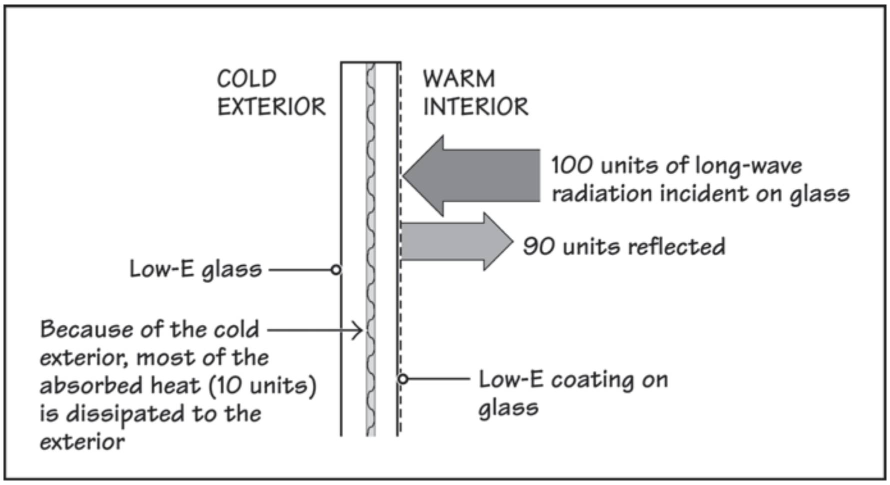

COLD EXTERIOR
WARM INTERIOR
100 units of long-wave radiation incident on glass
90 units reflected
Low-E glass
Because of the cold exterior, most of the absorbed heat (10 units) is dissipated to the exterior
Low-E coating on glass

FIGURE 30.18 Long-wave radiation absorbed by low-E glass from a warm interior and its dissipation. Observe that the majority of interior heat returns to the interior.

of the visible radiation, but it is more efficient in blocking the transmission of the infrared and ultraviolet parts of solar radiation by absorbing and/or reflecting them. Both a reflective coating and tinting of the glass, on the other hand, are clearly visible because they reflect or absorb the visible solar radiation, respectively.

The process of producing low-E glass is exactly the same as that of producing a reflective glass, that is, by depositing a metal or a metal oxide coating on one of its surfaces, either by magnetic sputtering or pyrolytic deposition.

The sputtered coating has lower abrasion resistance than the pyrolytically deposited coating but gives a lower E value—nearly 0.10. Low-E glass produced by the pyrolytic process has an E value of nearly 0.3. Because of its lower abrasion resistance, the sputtered coating is referred to as a *soft-coat low-E* coating and the pyrolytic coating is referred to as a *hard-coat low-E* coating. Sputtered-coated low-E glass can be used only in an insulating glass unit where the coating is applied to either surface 2 or surface 3 of the unit.

30.6 INSULATING GLASS UNIT (IGU)

In Section 5.6, it was noted that the R-value of a glass sheet is approximately 1.0, which is provided almost entirely by the inside and outside surface resistances. This is an extremely low value compared to the value of the opaque portions of a wall. That is why most heat loss or gain in a building occurs through glazed areas.

Because air is a good insulator, the R-value of glass can be increased by providing an (air- or gas-filled) space between two sheets of glass. To avoid problems with cleaning the surfaces of glass facing into this space, it is necessary that the intervening space be hermetically sealed. An unsealed space traps dust and moisture, both of which fog the view through the glass.

A sealed assembly consisting of two glass sheets with an intervening space is called an *insulating glass unit* (IGU). The most commonly used IGU in commercial construction is a 1-in. unit, in which the total width of the unit (the thickness of the two glass sheets plus the width of the space) is 1 in. In this unit, the width of the intervening space varies, depending on the thickness of the glass. If the two sheets of glass are each $\frac{1}{4}$ in. thick, the width of the intervening space is $\frac{1}{2}$ in. If the thickness of each glass sheet is $\frac{3}{16}$ in., the width of the intervening space is $\frac{5}{8}$ in. In residential windows, a $\frac{5}{8}$-in.-thick IGU (instead of a 1-in.-thick IGU) is generally used.

The construction of an IGU is shown in Figure 30.19. It consists of two sheets of glass with a spacer, which is sealed to the glass at the sides—the primary seal. The entire assembly is further sealed around all four edges—the secondary seal. The intervening space is filled with dry air or a gas.

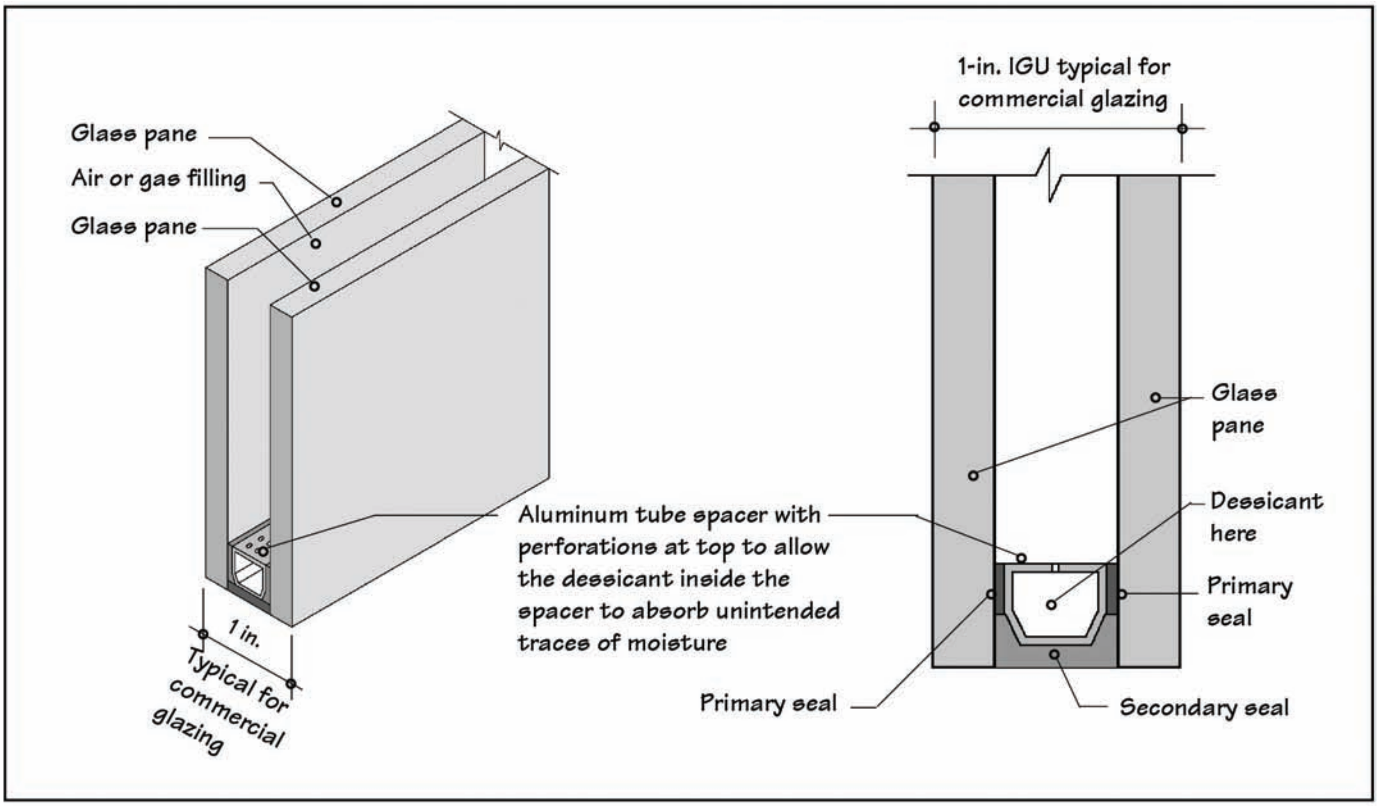
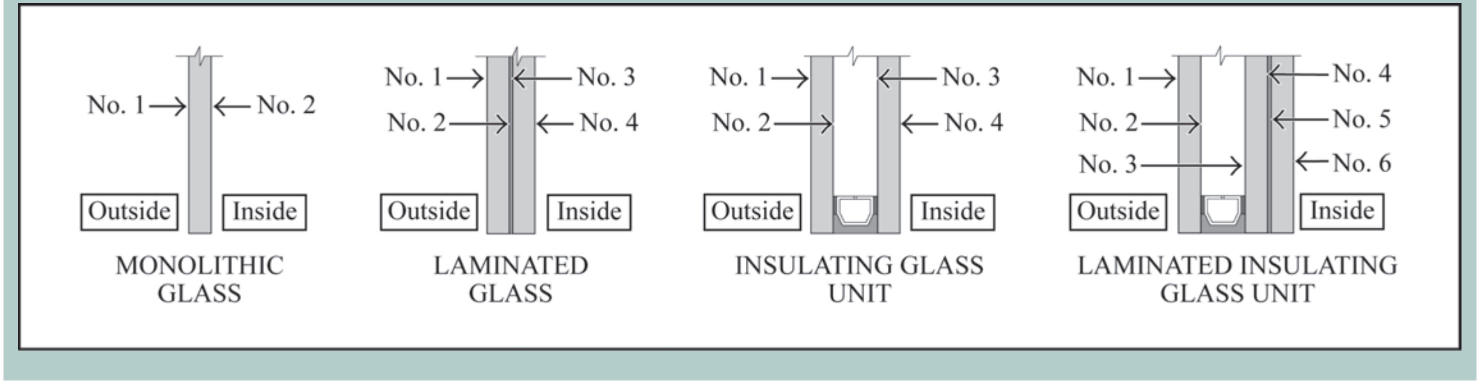

Glass pane
Air or gas filling
Glass pane
1 in.
Typical for commercial glazing
Aluminum tube spacer with perforations at top to allow the dessicant inside the spacer to absorb unintended traces of moisture
1-in. IGU typical for commercial glazing
Glass pane
Dessicant here
Primary seal
Primary seal
Secondary seal

FIGURE 30.19 Anatomy of an insulating glass unit (IGU). Although an aluminum spacer has been shown here, less conducting spacers are available that increase the R-value of the IGU.

EXPAND YOUR KNOWLEDGE

Standard Surface Designation of Glass

Because contemporary window and curtain wall glass is generally not a single sheet of glass but a fabricated product with coatings, laminations, and gas or air filling, it is necessary to have a standard numbering system for various surfaces. The glass industry has adopted a numbering system for the surfaces of various glass products, as shown in the following images. Note that the number sequence starts from the exterior surface of glass. Only the glass surfaces carry a number. The surfaces of laminations or coatings are not numbered.



However, as an extra precaution, the metal spacer is filled with a desiccant to absorb any incidental moisture that may not have fully evacuated from the intervening space. The spacer may be of a clear silvery finish or any other required color.

Because argon has a higher insulating value than air (see Table 5.2), many manufacturers provide argon-filled units. Krypton is another gas that is used as a filling in IGUs. Krypton has better insulating properties than argon but is more expensive. Some IGU manufacturers use a krypton-argon mixture.

Air, argon, or krypton is filled in the intervening space with the pressure of 1 atm to prevent any loading of glass due to pressure differences. Note that if a vacuum were to replace the air or gas filling, the glass would be subjected to the atmospheric pressure (nearly 2,100 psf), which is several times greater than the wind load expected on a window glass, even in the worst possible hurricane.

30.7 R-VALUE (OR U-VALUE) OF GLASS

Knowing that the R-value of a single sheet of glass is approximately 1.0, the approximate R-values (or U-values) of other glass products can be obtained with reference to Table 30.1. Manufacturers' data must be consulted for precise values.

Note that a tinted glass has the same R-value as a clear glass and a reflective coating improves the R-value of a glass only slightly.

As Table 30.1 shows, one air space adds 1.0 to the R-value of glass. Thus, an IGU with one air space has an R-value of nearly 2.0. (1.0 for the R-value of the inside and outside surface resistances and 1.0 for the R-value of the air space. The two sheets of glass add negligibly to the total R-value of the unit.) The U-value of this unit is approximately 0.5, Figure 30.20. The R-value of an IGU with two air spaces is approximately 3.0 ($U = 0.33$).

A low-E coating adds an R-value of approximately 1.0 to the unit. Thus, a low-E-coated IGU with one air space has an R-value of nearly 3.0 (1.0 for the R-value of the inside and outside surface resistances, 1.0 for the R-value of the air space, and 1.0 for the low-E coating). The U-value of this unit is 0.33.

A reflective coating also helps to reduce the U-value of glass to a small extent because a reflective coating is of a material similar to that of the low-E coating. As Table 30.1 shows,

TABLE 30.1 ADDITION TO THE R-VALUE OF GLASS BY VARIOUS ITEMS

Item	Contribution to R-value of glass
Air-filled space	1.0
Argon-filled space	1.6
Low-E coating	1.0
Reflective coating	0.2
Glass tint	0.0

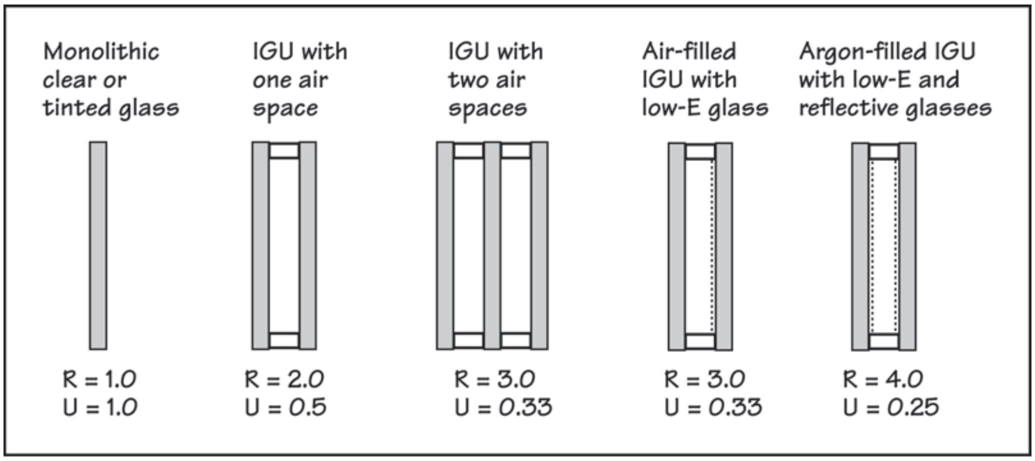


FIGURE 30.20 Approximate R-values (and U-values) of various types of IGUs. Note that the U-value is the inverse of the R-value.

the contribution of a reflective coating to the R-value is approximately 0.2. Thus, a reflective-coated monolithic glass will have an R-value of nearly 1.2 (U-value = 0.83). Note that the tinting of glass does not change its U-value.

Argon-filled units have lower U-values compared with units that contain air. Argon filling adds an R-value of approximately 1.6 to the unit. Thus, an argon-filled, low-E-coated reflective IGU has a total R-value of nearly 3.8 (1.0 for the internal and external surface resistances, 1.6 for the argon-filled space, 1.0 for the low-E coating, and 0.2 for the reflective coating).

An increase in the R-value of a glass product beyond 4.0 can be achieved only by adding a second intervening space in the IGU, but if this is accomplished by adding a third sheet of glass, it makes the unit heavier and costlier. One manufacturer makes a low-E IGU by using a patented system in which a clear plastic film is suspended halfway into the intervening space, Figure 30.21.

The film divides one space into two spaces, decreasing the U-value of the unit without making it heavier. The low-E coating is placed on the plastic film. Being transparent, the film is not visible, so that the unit is virtually indistinguishable from the standard one-intervening-space unit. The R-value of this unit with an argon filling is reported to be approximately 5.0, and it is 6.0 with a krypton filling.

Because of the plastic in the intervening space, this unit has a limited ability to withstand high temperatures. IGUs with two low-E-coated plastic films and krypton filling (giving three spaces) are available with an R-value of approximately 8.0.

NOTE

Location of a Low-E Coating in an IGU

A low-E coating is generally placed on the interior glass pane of an IGU (on surface 3). This location works well for cold climates because the low-E coating reflects the interior heat back.

For warm climates, a low-E coating is generally placed on the exterior glass pane of an IGU (on surface 2), which reduces the inward emission of solar heat absorbed by the exterior pane. However, if the IGU must also have a reflective coating, it is placed on surface 2 and the low-E coating is placed on surface 3. In this location, the low-E coating reflects the heat from the intervening space back to the exterior.

U-VALUES FOR SUMMER AND WINTER CONDITIONS

In the previous discussion, we have assumed that the U-value of glass is constant for a given type of glass or an IGU. In fact, the U-value of glass depends, to some extent, on the external and internal environmental conditions. Thus, glass manufacturers quote separate U-values for summer and winter conditions. The difference between the two values is significant only if a detailed analysis of the energy performance of a building is needed.

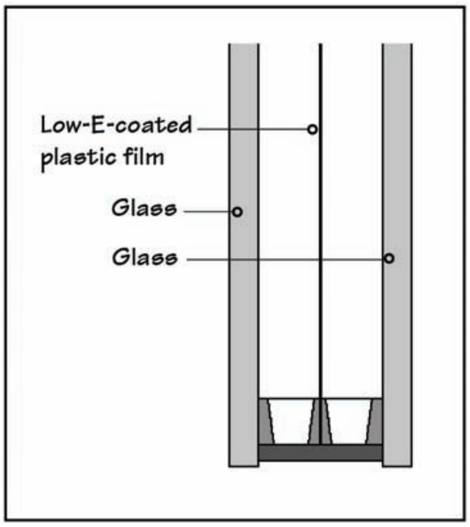


FIGURE 30.21 An IGU with a low-E-coated plastic film in air-filled or argon-filled space.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

11. Tinted glass absorbs more solar radiation than clear glass.
a. True
b. False

12. If the reflective coating on tinted glass is on the interior surface of the glass, the solar radiation absorbed by the glass is greater than if the same coating is on the outside surface.
a. True
b. False

13. When solar radiation falls on a glass, a certain amount of solar energy enters the enclosure through the glass. A commonly used measure of solar heat gain through the glass is called
a. VT.
b. SHGC.
c. UVT.
d. CRF.
e. none of the above.

14. Before a reflective coating is applied on a glass, the glass must first be cut to size.
a. True
b. False

15. Which of the following indices measures the effectiveness of the transparency of glass in relation to the solar heat gain through glass?
a. UVT
b. SC
c. SHGC
d. LSG
e. None of the above

16. A reflective coating increases the R-value of glass only marginally.
a. True
b. False

17. An IGU is
a. an assembly of two glass sheets.
b. an assembly of two glass sheets with an intervening space.
c. a sealed assembly of two glass sheets with an intervening space.
d. a sealed assembly of two glass sheets with an intervening space and a spacer.
e. none of the above.

18. Which type of gas is used in an IGU?
a. Air
b. Argon
c. Krypton
d. All of the above
e. None of the above

19. To obtain an IGU with a high R-value, the space between the glass sheets should be
a. air filled.
b. argon filled.
c. hydrogen filled.
d. none of the above.

20. Surface 3 in an IGU is
a. the surface of the exterior glass sheet facing the exterior.
b. the surface of the interior glass sheet facing the interior.
c. the surface of the exterior glass sheet facing the intervening space.
d. the surface of the interior glass sheet facing the intervening space.

21. The approximate R-value of a clear glass sheet is
a. 1.0.
b. 2.0.
c. 3.0.
d. 4.0.
e. 5.0.

22. The approximate R-value of a tinted glass sheet is
a. 1.0.
b. 2.0.
c. 3.0.
d. 4.0.
e. 5.0.

23. The approximate R-value of an air-filled IGU is
a. 1.0.
b. 2.0.
c. 3.0.
d. 4.0.
e. none of the above.

24. The approximate R-value of an air-filled IGU with a low-E-coated glass is
a. 1.0.
b. 2.0.
c. 3.0.
d. 4.0.
e. none of the above.

30.8 GLASS AND GLAZING

The discussion of R-values given in the previous sections refers to glass only. In practice, however, we are interested in the R-value of glazing, which includes the glass and the frame in which the glass is held. The R-value of framing material (aluminum, vinyl, or wood) is not the same as that of glass. Therefore, the R-value of a glazing (a window or a curtain wall) is different from that of glass alone.

The overall R-value of glazing is obtained by averaging the R-values of its three parts: the center of the glass, the edge of the glass, and the frame. The center of the glass constitutes most of the glazing, Figure 30.22. The R-value of the center of the glass is the R-value of the glass itself. The approximate R-values given in Figure 30.20 refer to the R-values of the center of the glass.

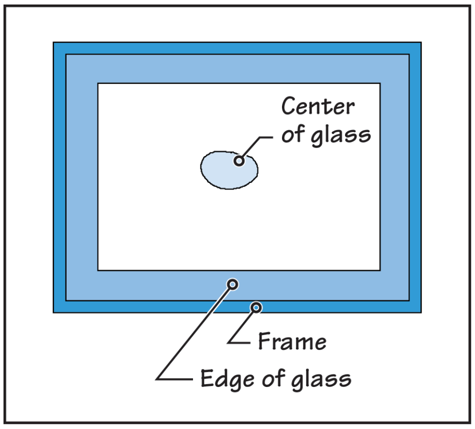


FIGURE 30.22 Three parts of a typical glazing (center of the glass, edge of the glass, and frame) that contribute differently to heat flow.

The edge of the glass is an area surrounding the frame, which has a width of approximately 2.5 in. A greater amount of heat is conducted through this area than through the center of the glass because of its proximity to the frame (and the presence of the aluminum spacer in an IGU).

Therefore, the size of the glazing affects its R-value. A small aluminum window generally has a lower R-value than a large window, although the materials used in both windows may be the same. This is due to the relatively larger area of the frame and edges in a small window. In commercial curtain walls, where the framing members are spaced farther apart, the difference between the R-values of the glass and the glazing is smaller than that of a window.

THERMAL BREAK IN ALUMINUM FRAMES

The R-value of the frame depends on the dimensions of the frame, its material, and its configuration (i.e., whether or not there is a thermal break in the aluminum frame). A thermal break consists of an insulating connector (usually polyurethane) that connects the two parts of the aluminum frame, Figure 30.23. Polyurethane has excellent rigidity and strength to function as framing material.

The frames of most aluminum windows used in contemporary commercial construction are thermally broken. The use of a thermal break in aluminum window and glass curtain wall frames has improved the R-values of glazing in addition to reducing the condensation potential. Condensation is formed on the outside surface of the aluminum window (or glass curtain wall) frames in cold climates as the warm, humid inside air exfiltrates from around the gaskets in glazing pockets. Because of their ability to eliminate or reduce this type of condensation, thermally broken window (or glass curtain wall) frames are more important for cold, northern U.S. climates than for warm climates. A large amount of condensation formed on tall buildings can be a great hazard to pedestrians with the frozen condensate falling on the ground.

LOW-CONDUCTIVITY SPACER IN AN IGU

Another factor that affects the R-value of glazing is the type of spacer used in an IGU. Traditionally, the spacer in an IGU consisted of a perforated rectangular aluminum tube. The perforations and the desiccant material within the tube help absorb any unintended moisture in the unit (Figure 30.19). Recently, spacers, which are thermally less conducting than the aluminum tube, have been introduced. These consist of a U-shaped aluminum spacer (instead of a tube), plastic, or a plastic foam spacer. The technology related to producing more efficient spacers is called *warm edge technology* (WET).

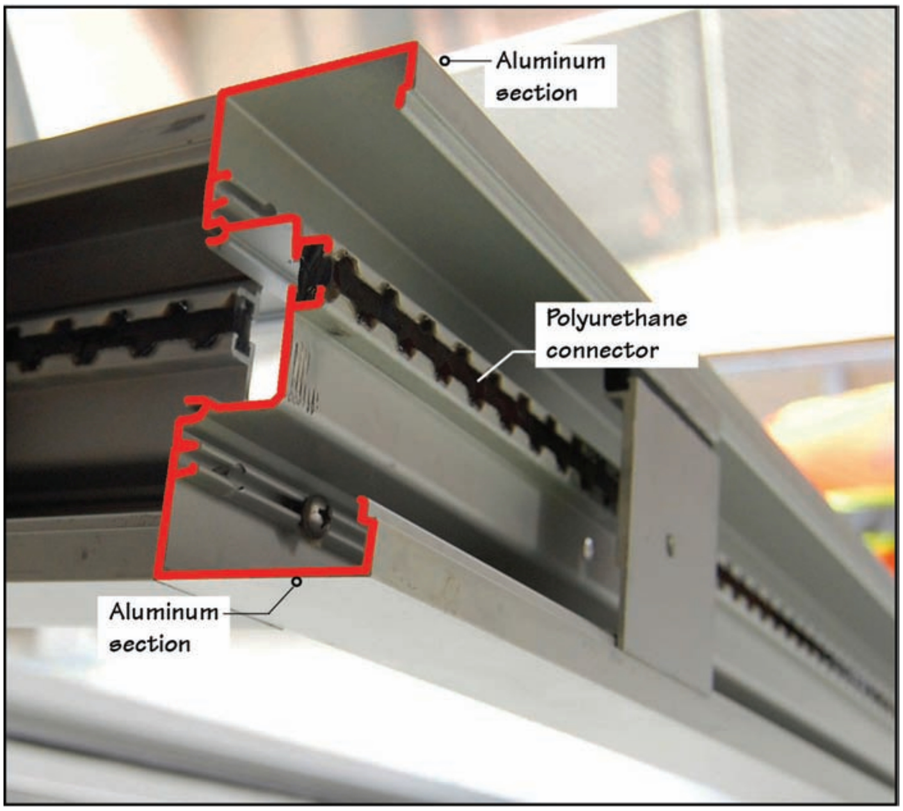


FIGURE 30.23 A composite aluminum window section formed of two split sections (profiles highlighted in red color) that are connected together with polyurethane-based compound. Polyurethane provides a thermal break between the two split sections because the thermal resistivity of polyurethane is more than one thousand times that of aluminum. One split section forms the inside part of the window and the other forms its outside part. The composite section is made by placing the two sections adjacent to each other and filling the gap with liquid polyurethane. The strength of cured polyurethane connector is comparable with that of aluminum.

CONDENSATION RESISTANCE FACTOR (CRF) OF GLAZING

Because the R-value of glazing is fairly low compared with that of the opaque portions of a wall, condensation on the interior surface of the glass or its frame can readily occur when the outside temperature is low and the interior relative humidity is moderate to high. A measure that rates a glazing for its condensation potential is called the *condensation resistance factor* (CRF); see the second Principles in Practice section at the end of this chapter.

30.9 SAFETY GLASS

Because of the transparency of glass, a large glazed opening without an intermediate horizontal framing member may be mistaken for a clear (unglazed) opening. In this situation, there is a likelihood that a person may unwittingly attempt to walk through the glass, thinking that it is a clear opening. In this and several other situations, the use of annealed glass is hazardous because of the sharp pieces it produces on breaking.

Building codes require the use of safety glass in locations where accidental human impact is expected. Such locations are called *hazardous locations*. Some examples of hazardous locations are shown in the adjacent note. Two types of glass are considered to be safety glass:

- Fully tempered glass
- Laminated glass

They provide safety in different ways. On impact, tempered glass breaks into small, blunt, relatively harmless pieces. Laminated glass, on the other hand, is safe because it stays in place after breaking due to the plastic interlayer. The building codes require that safety glass should be identified with an irremovable label, Figure 30.24.

Not all tempered or laminated glass is safety glass. To be recognized as such, the glass must comply with the appropriate test standards. In this test, the glass specimen is mounted in a test frame, Figure 30.25. The test frame has an impactor suspended from the top. The impactor,

NOTE

Hazardous Locations

Some examples of hazardous locations in buildings requiring safety glass are given here. For a comprehensive list and description, refer to the building code.

- Glass in a swinging door
- Glass in panels of a sliding door and a bifold closet door
- Glass in a door and enclosure for a hot tub, whirlpool, sauna, steam room, bathtub, and shower
- Glass in some fixed conditions adjacent to a glass door
- Glass in guardrails

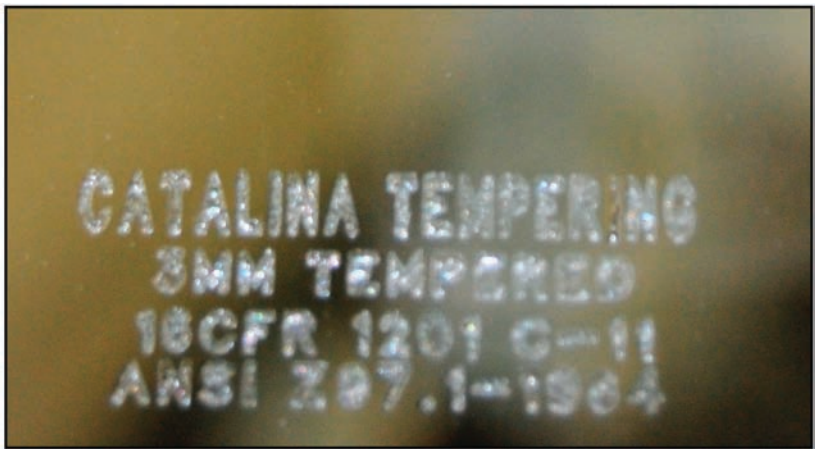
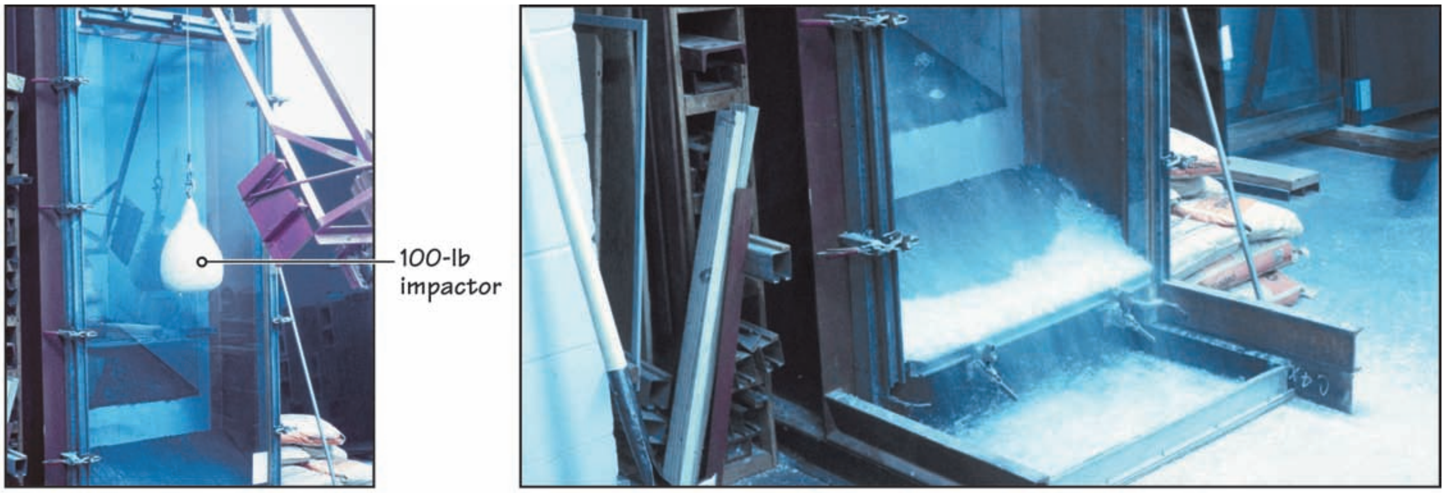


FIGURE 30.24 A typical label etched on a tempered glass sheet, giving the name of the tempering facility, glass thickness, and the standard to which the tempered glass complies. The International Building Code requires that the safety glass be so identified with acid etching, sand blasting, ceramic firing, or be of a type that cannot be removed without being destroyed. Because a tempered glass cannot be subjected to any one of the above treatments after tempering, the label is applied on the glass before tempering. "16 CFR 1201" is the safety standard for architectural glazing promulgated by the U.S. Consumer Product Safety Commission (CPSC).



(a) Specimen glass in the test frame, which is about to receive the impact

(b) Glass after the test. The size of broken glass pieces (which must be small enough and within the limits specified in the test standard) indicate that the glass has passed the test.

FIGURE 30.25 Testing a tempered glass specimen to verify that it conforms to the requirements for a safety glass.

which weighs 100 lb, consists of a leather punching bag filled with lead shots. The impact on the test specimen is produced by moving the impactor away from its rest position and releasing it.

The test simulates the impact of a person running into a glazing. Although 100 lb is less than the average weight of a human being, it is considered adequate because, in an impact with a glazing, the entire weight of the person is not likely to be involved. The glass is assumed to have passed the test if the specimen satisfies the breakage criteria outlined in the test standard. Building codes require that every pane of tempered glass used in hazardous locations bear a label identifying its compliance with the test.

30.10 LAMINATED GLASS

In its simplest form, laminated glass is made from two layers of glass laminated under heat and pressure to a plastic interlayer so that all three layers are fused together, Figure 30.26. In the event of an impact, the glass layer in laminated glass may break, but it will not fall out of the frame. The glass tends to remain bonded to the interlayer, minimizing the hazard of shattered glass.

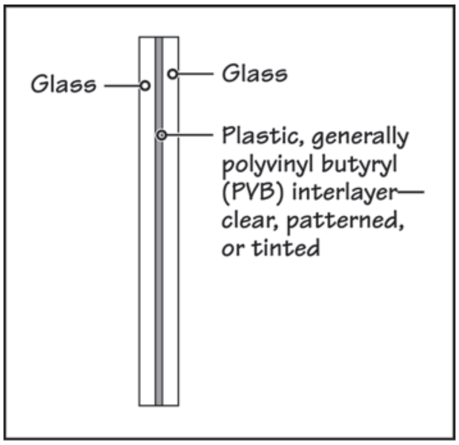

Glass
Glass
Plastic, generally polyvinyl butyryl (PVB) interlayer—clear, patterned, or tinted

FIGURE 30.26 Section through a laminated glass sheet.

Laminated glass has been used for automobile windshields for a long time. In architectural applications, it is the product of choice for skylights, sloped and overhead glazing, zoos, and aquariums. Because the glass remains in the opening even after breakage, laminated glass is also recommended for windows in earthquake-prone areas to reduce injury from abrupt shattering of glass.

The plastic interlayer, generally polyvinyl butyryl (PVB), may be clear, patterned, or tinted. It comes in three standard thicknesses: 15 mil, 30 mil, and 60 mil. Where greater safety or security is required, a thicker interlayer (90 mil or thicker) or multiple layers of thinner sheets may be used.

A major advantage of the plastic interlayer is that it also blocks out most of the ultraviolet radiation. The plastic interlayer also improves the sound-transmission properties of glass. Any type of glass—annealed, heat strengthened, or tempered—can be used in making laminated glass. Laminated glass can also be used in IGUs.

LAMINATED GLASS AS SAFETY GLASS IN HAZARDOUS LOCATIONS

If used in hazardous locations, laminated glass must pass the same impact-resistance test as tempered glass. Additionally, it must pass the boil test. The boil test determines the ability of glass to withstand resistance to high temperatures. In this test, 12-in. by 12-in. specimens of laminated glass are immersed in boiling water for 2 h. The specimens are deemed to have passed the test if no bubbles or other defects more than $\frac{1}{2}$ in. from the outer edges of the glass develop.

HURRICANE-RESISTANT AND BLAST-RESISTANT GLASS

With a suitable thickness of PVB lamination, laminated glass can be made to resist the impact of wind-borne missiles and is mandated for openings in hurricane-prone coastal regions. Blast (explosion)-resistant laminates are also available, and blast-resistant glass is commonly specified to meet higher security requirements. Tempered glass can be laminated, and laminated-tempered glass can be used in IGUs.

30.11 STRUCTURAL PERFORMANCE OF GLASS

Glass is a brittle material; that is, a glass pane will fail at a relatively low deflection. As previously stated, glass is weak in tension and bending but relatively strong in compression.

Although glass is sometimes used in structural applications, such as small floor slabs and stair treads (see Chapter 35), its primary use is in nonstructural applications, such as windows, skylights, and guardrails. Therefore, glass is not considered a structural material like steel, wood, concrete, and masonry.

Glass in windows is required to resist wind, earthquake, and thermal loads. Glass in skylights must be able to withstand snow loads, loads due to repair personnel, and wind and earthquake loads. Glass in the rear walls of squash and racquetball courts is subjected to impact loads, and the glass used in aquariums must be able to withstand hydrostatic pressure. All of these loads cause bending in glass. Thus, the most important structural property of glass that is of interest to us is its bending strength.

Unlike other materials, the strength of glass is statistically complex because every glass sheet has numerous randomly distributed microscopic internal cracks and other flaws.

Furthermore, the edge conditions of glass also affect its strength. Clean-cut edges provide the maximum strength. If the edges are damaged, the ability of the glass to resist loads is reduced. Thus, the actual breakage of glass results from a complex interaction between the size, orientation, distribution, and severity of cracks and edge defects.

Consequently, the strength of an individual glass pane cannot be predicted with reasonable accuracy. In other words, if several identical panes of glass are tested, there will be an unusually large variation in their breaking loads. Therefore, the strength of a glass pane is expressed in terms of the *probability of breakage* under a given load, that is, the number of panes that are likely to break per 1,000 panes. Thus, a probability of breakage of $\frac{3}{1,000}$ (three per thousand) means that 3 out of a total of 1,000 panes will probably break when a specified load is placed on the panes for the first time.

The maximum probability of breakage allowed by building codes for determining the glass thickness in windows and curtain walls to withstand wind loads is $\frac{8}{1,000}$. A lower probability of breakage may be required for glass in high-rise and other critical buildings.

ASTM Standard E 1300, "Standard Practice for Determining Load Resistance of Glass in Buildings", provides an authoritative procedure for determining the glass thickness to resist a given wind load.

HIGHER STRENGTHS OF HEAT-STRENGTHENED AND TEMPERED GLASS

As noted previously, tempered glass is nearly four times stronger than annealed glass. This implies that a tempered glass pane can withstand four times as much load as an annealed glass pane of the same thickness and size. However, the modulus of elasticity of tempered glass (and heat-strengthened glass) is the same as that of annealed glass. This implies that the deflection of tempered glass and annealed glass panes of the same size and thickness will be equal under a given load. Thus, if tempered glass is made to withstand a greater wind load because of its higher strength, greater deflection will be produced in the panes. This will place greater pressure on gaskets and seals, leading to their premature failure. It may also expel the glass out of the opening.

Therefore, in practice, tempered glass and heat-strengthened glass are designed to withstand the same wind load as annealed glass. In other words, the higher strengths of tempered glass and heat-strengthened glass are usually not exploited. Tempered glass and heat-strengthened glass are used primarily for their greater impact resistance, greater thermal stress resistance, and safer breakage pattern.

30.12 FIRE-RESISTANT GLASS

Ordinary glass (whether annealed, tempered, or laminated) is not resistant to fire. When subjected to a typical building fire, it shatters in 2 or 3 min. The types of glass commonly used as a fire-resistant glass are:

- Wired glass
- Intumescent multilaminate glass
- Intumescent gel-filled glass units

WIRED GLASS

Wired glass is made by the rolling process, not by the float-glass process. During the rolling process, welded wire mesh (which looks like chicken wire mesh) is embedded in the middle of the glass thickness so that the resulting product is a steel wire—reinforced glass, Figure 30.27. The wire diameter is nearly 0.020 in.

The minimum thickness of glass recognized as fire-rated glass is $\frac{1}{4}$ in. When subjected to fire, wired glass also breaks in 2 to 3 min, but unlike annealed glass, which falls out of the frame, wired glass is held within the opening because of the wire mesh, and hence contains the spread of smoke and other fire gases.

Because of the embedded wires, wired glass is often confused with safety glass, which it is not. Unlike tempered glass, wired glass is not impact resistant. Additionally, its bending strength is only half that of annealed glass. On impact, wired glass breaks into sharp pieces, and the broken wires will generally project out of the glass, causing injury to a person. The wires can even act as a spider web on human impact and catch a victim rather than permit the person to pass through safely. Thus, although wired glass is fire resistant, it is not a safety glass.

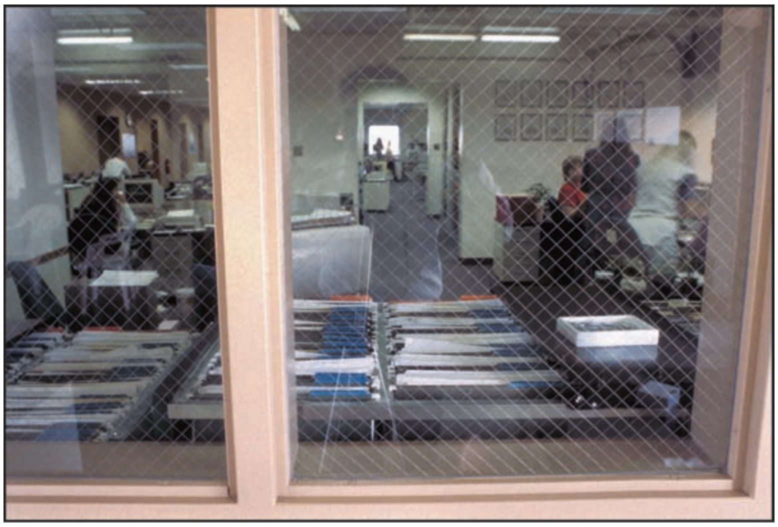


FIGURE 30.27 Wired glass in a fire-rated window between a parking garage and an office room.

INTUMESCENT MULTILAMINATE GLASS

Intumescent multilaminate glass (IMG) consists of multiple sheets of annealed glass alternated with intumescent interlayers. The number of glass and intumescent layers determine the fire rating. A fire rating of up to 2 h is attainable. When fire occurs, the intumescent layers become opaque and expand to provide the fire resistance.

INTUMESCENT GEL-FILLED GLASS UNITS

Intumescent gel-filled glass is an IGU in which the intervening space is filled with a clear gel. In the case of fire, the gel absorbs the heat, transforming the glass into a heat-insulating opaque crust.

A unit consisting of two sheets of $\frac{1}{4}$-in.-thick tempered glass with $\frac{3}{8}$-in. gel provides a $\frac{1}{2}$-h fire rating. The same construction with $1\frac{1}{8}$-in. gel provides a 1-h rating. A 2-h rating is obtained by a unit with two gel spaces of $1\frac{1}{4}$ in. and three sheets of glass. Under normal conditions (when there is no fire), this product looks like any other IGU with clear glass panes. These units can also be obtained to serve as safety glazing.

30.13 PLASTIC GLAZING

Clear plastic sheets (referred to as *light-transmitting plastics*) have gained popularity in some applications as an alternative glazing material. Three important advantages of plastic over glass are as follows:

- Plastic can be bent to curves far more easily than glass. Plastic is the material of choice in curved skylights, particularly doubly curved shapes such as domes.
- Plastic is several times stronger than glass of the same thickness and is also more impact resistant. It does not shatter or crack like glass. It is, therefore, specified in fenestration where glass breakage due to vandalism is a concern or where a high degree of security is required.
- Plastic glazing is lighter than glass.

However, the disadvantages of plastic glazing far outweigh its advantages. That is why its use is limited to applications where glass cannot be used. Some of the disadvantages of plastic glazing are as follows:

- Plastic has a much greater coefficient of thermal expansion than glass. If the movement of plastic glazing is restricted, it will visibly bow out in the direction of higher temperature. Framing details must, therefore, allow linear movement as well as the rotation of glazing. Consequently, framing details are more complex with plastic glazing, which further adds to its cost.
- Humidity changes also affect the dimensional stability of plastics. Plastic expands with increasing humidity, creating the same problems as thermal expansion.
- Plastic is not abrasion resistant, although abrasion-resistant coatings on plastic glazing considerably improve the abrasion resistance of plastics.
- Plastic is vapor permeable, so that sealed insulating units are not possible.

NOTE

Fire-Rating Limitations of Wired Glass

Building codes place severe limitations on the use of wired glass as a fire-rated glass: $\frac{1}{4}$-in.-thick wired glass can be used in an opening whose fire rating is between 60 and 90 min, provided that the area of wired glass is less than 100 in.^{2}. If the fire rating of the opening is 45 min, the maximum permissible area of wired glass is 9 ft^2 (1,296 in.^{2}). If the fire rating of a window is 20 min or less, the area of wired glass is not limited by the building codes.

For a fire-rated opening, both the wired glass and the opening must be so labeled by the manufacturers. Not every $\frac{1}{4}$-in.-thick wired glass is a fire-rated glass.

NOTE

Building codes and Plastic Glazing

Building codes place stringent restrictions on the use of light-transmitting plastics in wall and roof openings. Less stringent restrictions apply to buildings of Type V(B) construction (see Section 7.5 for an explanation of the types of construction).

- Plastic yellows with age (ultraviolet degradation), reducing its clarity and light transmission.
- The most serious disadvantage of plastic is its combustibility. It will contribute fuel to a building fire. Therefore, building codes place severe limitations on the area of plastic glazing and the height of the building above which it cannot be used.

ACRYLIC VERSUS POLYCARBONATE GLAZING

At the present time, two types of plastic are used for glazing: acrylic and polycarbonate. Acrylic has better resistance to ultraviolet radiation than polycarbonate. It yellows more slowly and has greater resistance to abrasion and scratching than polycarbonate. It also has greater resistance to chemicals such as household and glass cleaners.

Polycarbonate, on the other hand, has greater impact resistance than acrylic. It can withstand 30 times as great an impact as acrylic and 250 times as great an impact as glass, making it the most vandal-resistant glazing. Polycarbonate is, therefore, commonly specified for bus shelters and school windows where vandalism is a problem.

Polycarbonate can also withstand higher temperatures than acrylic. Therefore, polycarbonate is commonly used in signs that are exposed to high temperatures from light sources. Acrylic is commonly used in curved skylights and greenhouses, where greater durability and weatherability are required.

NOTE

Acrylic and Polycarbonate

Acrylic—more weather and chemical resistant; commonly specified for skylights and greenhouses

Polycarbonate—more vandal and heat resistant; commonly specified in bus shelters and glazing subjected to vandalism

30.14 GLASS FOR SPECIAL PURPOSES

There have been major advances in glass and glazing technology in recent years. A few of the glass types used for special purposes are described next.

SECURITY GLAZING

Security glass refers to a glass that is resistant to burglary, forced entry, and bullet penetration. Because the safety against these threats is a function of both the glass and the frame in which the glass is held, the term *security glazing* is commonly used rather than *security glass*. Typically, security glazing is composed of single or multiple panes of glass fused with single or multiple sheets of plastic, usually held in a steel frame.

Security glazing can be designed to withstand different levels of threat, including repeat assaults. For example, if the threat level is burglary, the design must consider repeated impacts from hand-held weapons such as hammers, crowbars, or bricks.

Ballistic threats of various levels can be accommodated, depending on the power of the firearms to be resisted. Ballistic glazing is designed to be shatterproof on the victim's side, because the shattering of glass on the victim's side can cause serious injuries. Ballistic glazing is generally specified for drive-in bank windows, armored vehicles, and any other application where a high degree of security is required.

RADIATION-SHIELDING GLASS AND PLASTIC

The ability of a building material to shield against radiation is generally a function of its density. The greater the density and the thicker the material, the greater its radiation-shielding capability. Metals, concrete, and masonry materials (provided that there are no cracks in concrete and masonry) provide excellent radiation protection.

However, lead—because of its highest density among building materials and its flexibility— is the most commonly used radiation-shielding material. Where transparency is not required, lead curtains are commonly used, and lead aprons are worn for additional protection.

Radiation-shielding glass is made by adding lead (usually in the form of lead oxide) to the same ingredients as those of soda-lime glass. Lead acrylic is made from lead-acrylic polymer. Lead glass and lead acrylic have much greater radiation-shielding potential than ordinary soda-lime glass.

DIMMABLE GLASS

Dimmable glass refers to glass in which the light-transmission characteristics change from an opaque to a transparent glass with the flick of a switch. It consists of two layers of glass with a plastic interlayer that encapsulates polymer-dispersed liquid crystals (PDLC). When an electric field is applied to PDLC, the crystals orient themselves to let the light through. In its natural state (i.e., without the electric current), the glass is opaque, Figure 30.28.

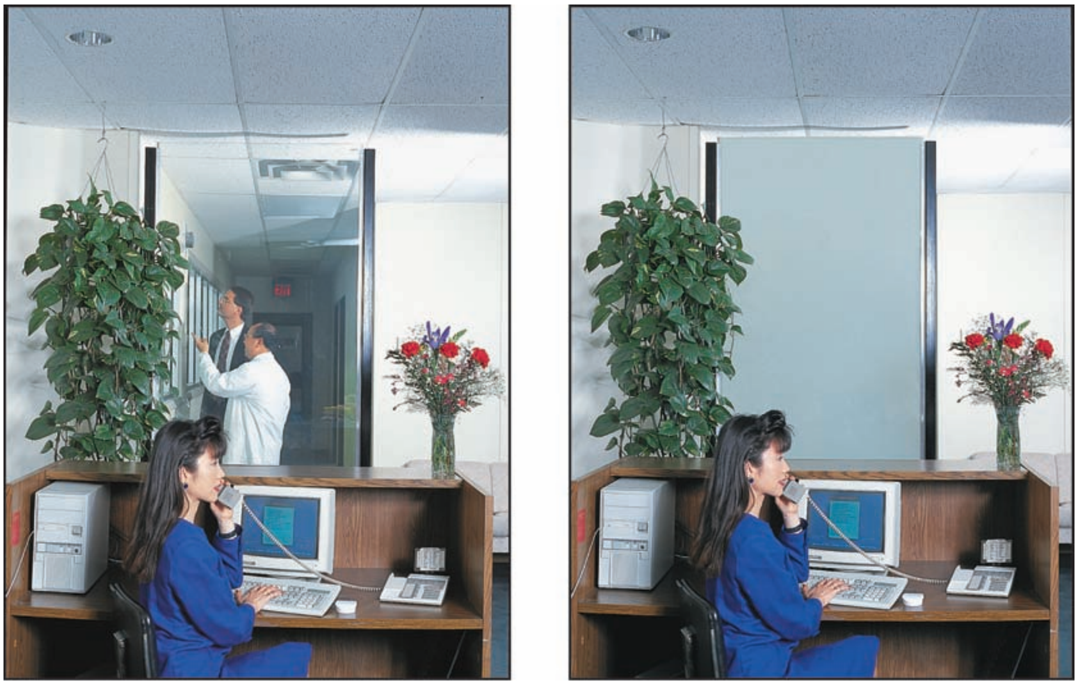


FIGURE 30.28 An example of the use of dimmable glass showing a glass pane that is transparent in the left-hand image and opaque in the right-hand image. (Photo courtesy of Polytronix, Inc.)

Also referred to as *electrochromic glass*, dimmable glass is used in situations where privacy requirements are changeable, such as conference rooms or executive offices. Although far more expensive than normal glass, it may be used in residential and office glazing for privacy and energy-conservation reasons. The switch mechanism can also be made automatic by a photovoltaic mechanism that responds to the ambient light environment. If the ambient light is excessive (e.g., due to direct solar radiation on the glass), the glass turns opaque. When the ambient light is low, the glass turns transparent.

SELF-CLEANING GLASS

A special oxide coating applied to one surface of the glass can make it self-cleaning. The coating breaks down organic dirt (due to trees, leaves, bird droppings, etc.) on the glass so that the glass is cleaned when rainwater falls on it. The coating does not affect inorganic dirt (e.g., plaster and paint droppings), which must be removed by conventional means. (The coating becomes active due to ultraviolet rays and may take nearly one week of ultraviolet exposure for a complete breakdown of organic dirt.)

30.15 CRITERIA FOR THE SELECTION OF GLASS

With so many factors to consider, the selection of glass, particularly for windows and curtain walls, is not an easy task. The selected glass must obviously be structurally adequate on its own. Additionally, the frame in which the glass is held must be adequate so that the entire glazing system is structurally adequate.

The safety of glass against human impact, the resistance of glass against wind-borne missiles, and the security of glass against blasts or bullets are other important considerations. These considerations apply to the glass as well as to the frame.

The energy performance of glass also plays an important role in its selection. As with structural and safety considerations, the energy performance of the entire glazing must be evaluated. To help designers, manufacturers of windows and curtain walls provide energy performance ratings of their products (see Chapters 31 and 32).

A checklist of factors that must be considered in the selection of glass for windows, curtain walls, and skylights is as follows:

- Structural adequacy—wind-load resistance, earthquake resistance (where needed), snow-load resistance (for skylights)
- Energy performance (U-value, SHGC, VT, LSG index, air infiltration, and CRF, as they apply to the entire glazing, are some of the important factors)
- Resistance to temperature-related stress
- Fire resistance, where needed

- Safety glass, where needed
- Blast resistance, where needed
- Missile-impact resistance and cyclic wind-load resistance in hurricane-prone areas
- Impact resistance in sports facilities (e.g., racquetball and squash courts)
- Radiation shielding, where needed

30.16 ANATOMY OF A GLAZING POCKET

In most glazing systems, the glass is captured by the framing members within a U-shaped pocket that is continuous on all four edges of the glass, referred to as the *glazing pocket*, Figure 30.29. Glazing pockets provide bearing and lateral load supports to glass. Additionally, they collect any incidental rainwater that might go past the glazing seals and weep it out.

Because the coefficient of thermal expansion of glass is different from that of the framing members, sufficient space must be left between the edges of the glass and the edges of the glazing pocket to allow the glass to move. Additionally, as the glass moves within the opening, it must not directly touch the frame but must be able to "float" within the opening. Important components of a glazing pocket are as follows:

- Setting blocks
- Edge blocks and (in seismic zones) corner blocks
- Glazing seals
- Weep holes

SETTING BLOCKS

Each pane of glass is supported on two identical *setting blocks*, generally at quarter points, Figure 30.30. Setting blocks serve two important functions: (a) they provide a hard, but resilient, bearing support to the glass, and (b) they lift glass up from the bottom of the glazing pocket to allow water to drain out from underneath and to prevent the glass from coming in direct contact with water. (The seals in an IGU and the PVB layer in a laminated glass are susceptible to damage by sustained contact with water.)

Neoprene, EPDM, and silicone are the materials commonly used for setting blocks. Generally, the setting blocks are rectangular in shape, but other profiles may be used as long as they allow sufficient clearance around the blocks for the passage of water.

EDGE BLOCKS

Edge blocks are used to separate the vertical edges of glass from the vertical frame members. Also referred to as *antiwalk blocks*, they cushion the glass from the frame and allow the glass to move within the opening without touching the frame. The movement of glass may be due to temperature changes or the effect of wind or earthquake forces. Corner blocks are required in addition to edge blocks in seismic zones.

GLAZING SEALS—WET-GLAZED AND DRY-GLAZED SEALS

Glazing seals are used within the glazing pockets to cushion the glass and help seal the glazing against air and water infiltration. One of the earliest glazing seals was *glazing putty*, also

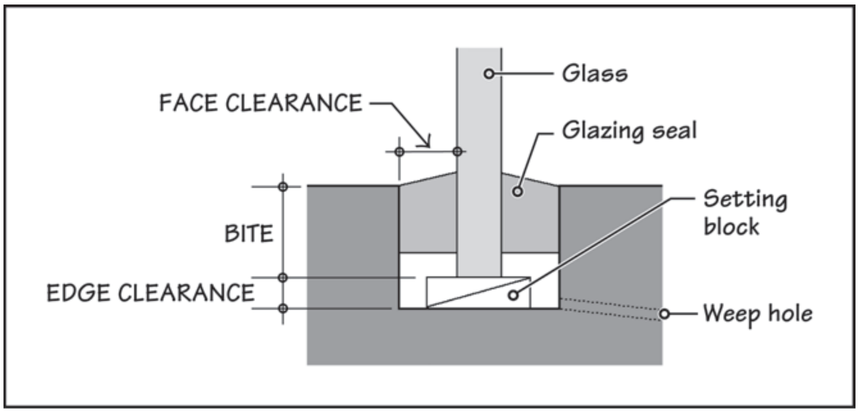


FIGURE 30.29 Glazing pocket and its components. Note that the dimensions of face clearance, edge clearance, and bite are controlled by industry standards.

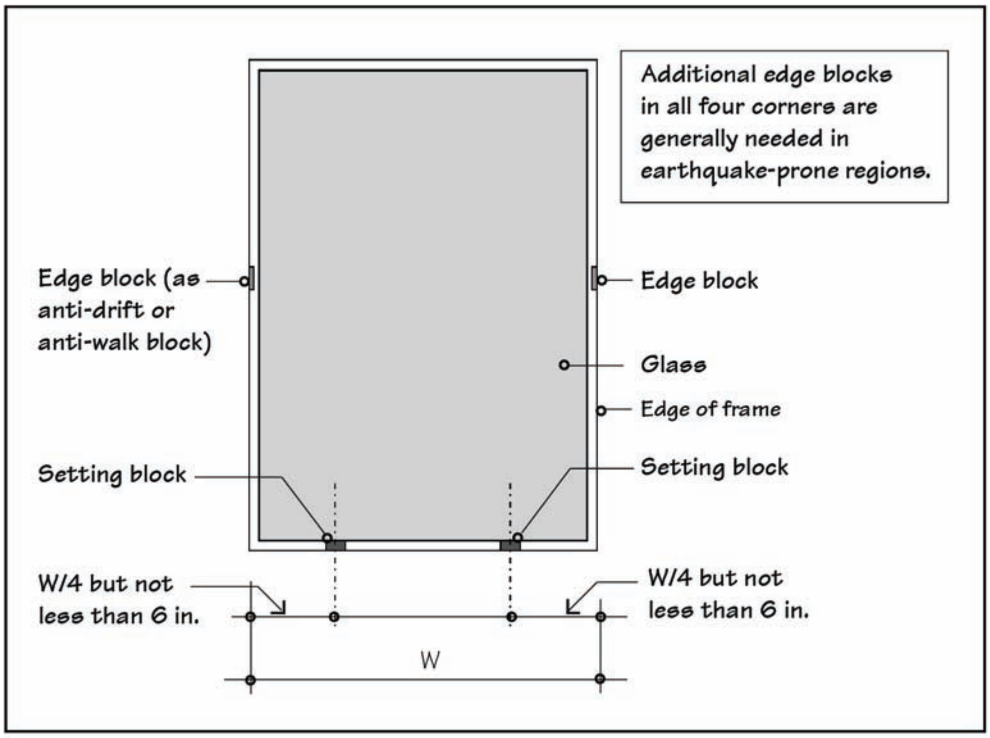

Additional edge blocks in all four corners are generally needed in earthquake-prone regions.
Edge block (as anti-drift or anti-walk block)
Edge block
Glass
Edge of frame
Setting block
Setting block
W/4 but not less than 6 in.
W/4 but not less than 6 in.
W

FIGURE 30.30 Setting blocks and edge blocks in a glazing. Both blocks are made of the same material.

called *glazing compound*. Glazing putty is made from linseed oil and powdered limestone. It was generally used in a rabbeted frame to function both as a seal and as a stop, Figure 30.31.

Glazing putty has largely been replaced by better glazing seals. Based on the glazing seal used, contemporary glazing is referred to as one of the following systems:

- Wet-glazed system
- Dry-glazed system
- Wet/dry-glazed system

A wet glazing seal consists of preshimmed double-sided tape, finished with elastomeric sealant bead applied above the tape. The sealant is tooled to slope away from the glass, Figures 30.32(a) and (b). Glazing putty (of earlier times) was an example of a wet glazing seal.

Dry glazing seals consist of *gaskets*. A gasket is generally made of neoprene, EPDM, or silicone rubber composite. Its material, size, and profile make it elastomeric, so that after installation, a gasket is under compression, clinging to the glass and the reglet to provide a seal. Therefore, it is also called a *compression gasket*.

Gaskets need some form of engagement into the frame. Therefore, gaskets are generally used with aluminum frames because, aluminum being a soft metal, can be easily profiled into a complex section to capture the gaskets. The part of the aluminum section that captures the gasket is referred to as a *gasket reglet*, Figure 30.32(c).

Dry glazing is more commonly used in contemporary glazing than wet glazing because the performance of dry glazing is less affected by workmanship, weather, and compatibility issues, Table 30.2. A wet/dry-glazed system is a combination of the two systems.

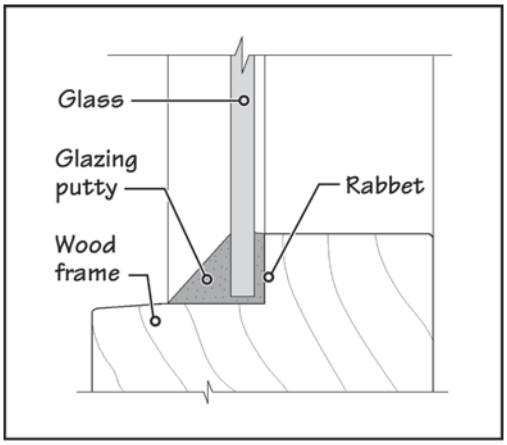
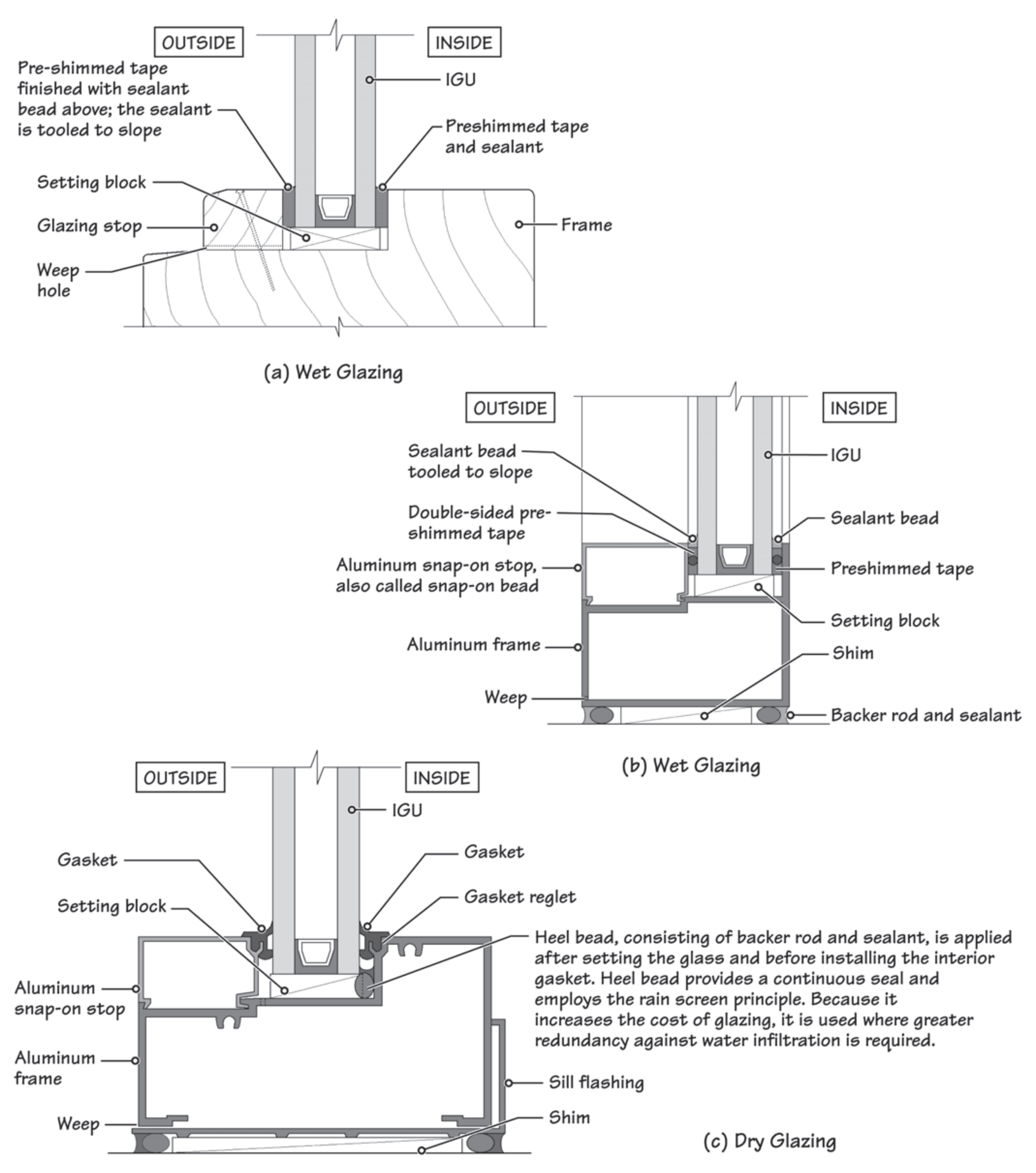

Glass
Glazing putty
Wood frame
Rabbet

FIGURE 30.31 In earlier wood and steel windows, glazing putty served both as a *stop* and as a seal.

The term stop in glazing literature is used for a member that holds the glass against the rabbet in the frame, providing lateral support to the glass. Thus, in this illustration, glazing putty serves as the stop.

The recess in the frame against which the glass is held is called a *rabbet*. The space between the stop and the rabbet constitutes the glazing pocket.


OUTSIDE
INSIDE
Pre-shimmed tape finished with sealant bead above; the sealant is tooled to slope
IGU
Preshimmed tape and sealant
Setting block
Glazing stop
Frame
Weep hole
OUTSIDE
INSIDE
Sealant bead tooled to slope
IGU
Double-sided pre-shimmed tape
Sealant bead
Aluminum snap-on stop, also called snap-on bead
Preshimmed tape
Setting block
Aluminum frame
Shim
Weep
Backer rod and sealant
OUTSIDE
INSIDE
IGU
Gasket
Gasket
Gasket reglet
Setting block
Heel bead, consisting of backer rod and sealant, is applied after setting the glass and before installing the interior gasket. Heel bead provides a continuous seal and employs the rain screen principle. Because it increases the cost of glazing, it is used where greater redundancy against water infiltration is required.
Aluminum snap-on stop
Aluminum frame
Sill flashing
Weep
Shim

(a) Wet Glazing

(b) Wet Glazing

(c) Dry Glazing

FIGURE 30.32 Examples of wet-glazed and dry-glazed seals.

TABLE 30.2 RELATIVE ADVANTAGES AND DISADVANTAGES OF DRY AND WET GLAZING SEALS

Type of seal	Advantages	Disadvantages
Wet glazing seal	Better resistance to water infiltration	Requires exterior and interior installation Performance dependent on workmanship Installation weather dependent More expensive
Dry glazing seal	Can be installed from the interior Less weather dependent Less dependent on workmanship Less expensive	Less watertight Gasket can shrink and create openings

RAIN-SCREEN PRINCIPLE APPLIED TO GLAZING POCKET

Regardless of whether dry glazing or wet glazing is used, some water may enter the glazing pocket due to poor workmanship or the degradation of the seals. Some window and curtain wall manufacturers recommend the use of the rain-screen principle to glazing pockets.

Because an air seal in the backup is an important component of a rain screen, the use of an additional continuous sealant bead and a backer rod in the glazing pocket, referred to as a *heel bead*, is recommended, Figure 30.32(c). A heel bead is applied in the glazing pocket after setting the glass and before applying the interior gasket.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

25. The R-value of an aluminum-framed glazing is generally
  a. higher than that of glass.
  b. lower than that of glass.
  c. equal to that of glass.

26. Laminated glass is
  a. an assembly of two glass sheets welded (fused) together into one sheet.
  b. an assembly of two glass sheets with an intervening space.
  c. a sealed assembly of two glass sheets with an intervening space.
  d. an assembly of two glass sheets fused together with a plastic interlayer.
  e. none of the above.

27. Which of the following statements is true about plastic glazing?
  a. It is stronger than glass.
  b. It is more vapor permeable than glass.
  c. It is less scratch resistant than glass.
  d. All of the above.
  e. None of the above.

28. The primary reason for the limited use of plastic glazing in buildings is that it is more expensive than glass.
  a. True **b.** False

29. Which type of glass is commonly used in drive-in bank windows?
  a. Annealed glass **b.** Tempered glass
  c. Laminated glass **d.** Heat-strengthened glass

30. Glass can be tempered as well as laminated; that is, laminated, tempered glass is available.
  a. True **b.** False

31. A glazing stop is used
  a. as a bearing support for glass.
  b. to seal the glass against water and air infiltration.
  c. to provide lateral support to glass.
  d. to provide a cushion between the glass and the glazing pocket.
  e. none of the above.

32. If the glass is sealed with preshimmed tape and sealant, the glazing is referred to as
  a. dry glazed. **b.** wet glazed.
  c. dry/wet glazed. **d.** wet/wet glazed.
  e. dry/dry glazed.

33. A heel bead is used in a glazing pocket.
  a. True **b.** False

34. A heel bead is used to
  a. increase the R-value of glazing.
  b. decrease the solar heat gain through glass.
  c. decrease water infiltration through glazing.
  d. increase the wind-load resistance of glazing.
  e. none of the above.

PRINCIPLES IN PRACTICE

Important Facts About Radiation

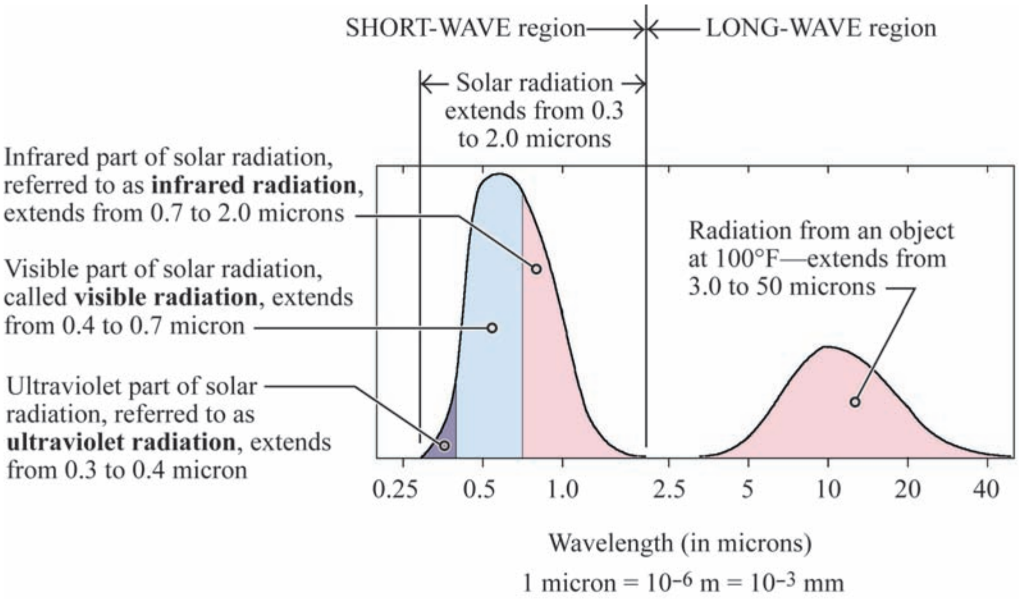
Radiation is emitted by all objects. Consequently, all objects receive radiation from other objects in their surroundings. In other words, a constant radiation exchange occurs between objects that have a direct line of sight between them (i.e., those that can see each other).

As the temperature of an object increases, the wavelength of radiation emitted by it becomes smaller. An object at a high temperature emits most of its radiation in short wavelengths. Conversely, an object at a low temperature radiates in long wavelengths.

A type of high-temperature radiation of interest is solar radiation. Although the actual temperature of the interior of the Sun is several million degrees Fahrenheit, solar radiation received on the Earth's surface has the same characteristics as the radiation from an object whose temperature is approximately 11,000°F (6,000°C).

Low-temperature radiation is present everywhere because it is emitted by objects on the surface of the Earth, such as the ground, sky, landscape elements, building surfaces, and furniture. The temperature of these objects seldom exceeds 150°F (60°C).

Because solar radiation is high-temperature radiation, it is referred to as short-wave radiation. The radiation from earthly objects, on the other hand, is long-wave radiation. This difference is shown in the following illustration, which gives the wavelength composition of solar radiation and radiation from an object at 100°F (38°C).



COMPONENTS OF SOLAR RADIATION (ULTRAVIOLET, VISIBLE, AND INFRARED RADIATION)

Observe that solar radiation extends from a wavelength of 0.3 μm to 2.0 μm. Approximately 3% of solar radiation lies in the ultraviolet region (wavelength less than 0.4 μm), 50% lies in the visible region (0.4 to 0.7 mm), and the remaining 47% lies in the infrared region. Radiation from an object at approximately 100°F (38°C) extends from a wavelength of nearly 3 to 50 μm.

The wavelength region up to 2.0 mm is generally referred to as the short-wave region, and beyond 2.0 mm, it is called the long-wave region. Building surfaces receive short-wave radiation only from the Sun. However, they receive long-wave radiation from all surrounding objects, including the sky, because they are at low temperature.

The radiation from the sky is low-temperature radiation because it is due to the heat contained in the atmosphere (air, dust, and water vapor particles). It is also referred to as diffuse solar radiation. The term solar radiation refers to the radiation contained in direct solar beams.

SURFACE EMISSIVITY, SURFACE COLOR, AND LONG-WAVE RADIATION

Building surfaces and objects behave differently to short-wave and long-wave radiation. As shown in Figure 30.13, a clear glass sheet transmits virtually all (85%) short-wave solar radiation. Having penetrated the glass, solar radiation heats room surfaces and the contents of the room. These objects, being at low temperature, emit long-wave radiation. Glass is virtually opaque to long-wave radiation because it absorbs 90% of it (Figure 30.16). Having absorbed the interior heat, glass dissipates part of it to the interior and part to the exterior by convection and radiation. In other words, glass does not allow the interior heat to escape as readily as it admitted the solar heat. This is the well-known greenhouse effect.

From Section 5.8, we know that the emissivity of a surface—a concept that applies only to long-wave radiation—is equal to its absorptivity. Thus, the reason glass absorbs nearly 90% of long-wave radiation is that its emissivity is 0.9.

A low-E surface absorbs little and reflects most long-wave radiation. A low-E coating on glass changes the behavior of glass in response to long-wave radiation. A reflective coating on glass, on the other hand, changes the behavior of glass with respect to solar radiation. It does not greatly affect the behavior of glass with regard to long-wave radiation.

Similarly, long-wave radiation does not discriminate between the colors of surfaces. Solar radiation does. A white- or light-colored surface is more reflective of solar radiation than a dark-colored surface. Long-wave radiation does not differentiate between the various colors.

PRINCIPLES IN PRACTICE

Condensation-Resistance Factor

The condensation-resistance factor (CRF) has been defined such that the higher its value, the better the performance of glazing with respect to condensation. The CRF of a glazing is obviously related to its R-value. The higher the R-value of glazing, the higher is its CRF. Thus, a window with an IGU has a higher CRF than one with a single sheet of glass.

The CRF of a window or curtain wall is obtained by measuring it in a test chamber. It is given in whole numbers. Manufacturers provide CRF values for their products. In choosing a glazing based on the CRF value, Table 1, which gives the minimum recommended CRF value of glazing based on the interior humidity and outside winter air temperature, is generally invoked. The inside temperature is assumed to be 68°F (20°C).

For example, according to this table, if the minimum winter air temperature at a location is 20°F (−11°C) and if the interior relative humidity of a building is 40% (typical of an office building), a minimum CRF value of 48 should be specified for the glazing in that building. In obtaining CRF values from Table 1, the outside air temperature is the design winter temperature of the location, defined as the temperature that is exceeded more than 97.5% of the time during December, January, and February.

Specifying a CRF value based on Table 1 does not ensure that no condensation will occur on the interior surface of glazing. It simply means that condensation will be minimal and within acceptable limits. CRF values below 35 are generally not specified.

TABLE 1 RECOMMENDED MINIMUM CRF VALUES OF GLAZING

This table is based on American Architectural Manufacturers Association (AAMA) Standard 1503-98 (revised 2004), "Voluntary Test Method for Thermal Transmittance and Condensation Resistance Factor of Windows, Doors, and Glazed Wall Sections".

The entry X in the table indicates that no test data are available in this standard.

The table is based on the interior temperature of 68°F (20°C) and outside wind speed of 15 mph.

		Inside relative humidity					
		15%	**20%**	**25%**	**30%**	**35%**	**40%**
	Outside air temperature	**Minimum CRF values**					
Minneapolis →	−20°F	45	52	57	62	X	X
Chicago →	−10°F	40	47	53	58	65	X
Boston →	0°F	32	40	47	52	58	63
New York →	10°F	17	30	37	45	52	57
Atlanta →	20°F	X	X			40	48

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

35. Building surfaces emit
- **a.** short-wave radiation.
- **b.** ultraviolet radiation.
- **c.** long-wave radiation.
- **d.** all of the above.
- **e.** none of the above.

36. Glass is virtually opaque to
- **a.** short-wave radiation.
- **b.** ultraviolet radiation.
- **c.** long-wave radiation.
- **d.** all of the above.
- **e.** none of the above.

37. Solar radiation is
- **a.** short-wave radiation.
- **b.** long-wave radiation.

38. A low-E glass is a poor reflector of long-wave radiation.
- **a.** True
- **b.** False

39. The condensation resistance factor (CRF) of glazing is directly related to
- **a.** the material used in framing members of glazing.
- **b.** whether or not reflective glass has been used in the glazing.
- **c.** whether or not tempered glass has been used in the glazing.
- **d.** the R-value of the glazing.
- **e.** all of the above.

40. The minimum value of the CRF generally specified is
- **a.** 55.
- **b.** 45.
- **c.** 35.
- **d.** 25.
- **e.** 15.

REVIEW QUESTIONS

1. Using sketches and notes, explain the process of manufacturing flat glass.
2. Using a sketch, explain why a tempered glass sheet is stronger than an annealed glass sheet.
3. What is heat-soaked glass and where is it used?
4. Using a sketch, explain the anatomy of an IGU.
5. Using a sketch, explain the standard surface designation system for (a) monolithic glass, (b) laminated glass, and (c) an IGU.
6. What is a low-E glass, and what are its benefits?
7. If low-E glass is used in an IGU, on which surface is the low-E coating placed, and why? Explain.
8. Explain how a low-E coating increases the R-value of glass.
9. Which type of glass would you recommend for the following locations?
   - **a.** Sliding-glass entrance door
   - **b.** Spandrel area of an all-glass curtain wall
   - **c.** Teller window of a drive-in bank

CHAPTER 31

Windows and Doors

CHAPTER OUTLINE

31.1 WINDOW STYLES

31.2 WINDOW MATERIALS

31.3 PERFORMANCE RATINGS OF WINDOWS

31.4 WINDOW INSTALLATION AND SURROUNDING DETAILS

31.5 CLASSIFICATION OF DOORS

31.6 DOOR FRAMES

31.7 FIRE-RATED DOORS AND WINDOWS

PRINCIPLES IN PRACTICE: A NOTE ON ALUMINUM

Not long ago, windows and doors could be made only from wood. Ornate carpentry was often used, and architects spent an inordinate amount of time and effort detailing the cross-sectional profiles of window and door frames, window sashes, door panels, and the related trims.

Because of the lack of automation and manufacturing technology, the carpentry and joinery related to window and door fabrication were carried out at the construction site. The performance requirements of windows and doors were modest at best and were directly related to the skill of the craftsperson building the window or door; good workmanship yielded higher-performing windows or doors. For windows, letting the daylight in and keeping the rainwater out were the only requirements. Because large sheets of glass were not available at that time, window glazing consisted of small panes of glass held by narrow horizontal and vertical wood members. For doors, the primary performance requirement was security.

Like most other building components, windows and doors have evolved over the years. Windows are now made not only from wood but also from aluminum, steel, vinyl, and fiberglass. Additionally, two materials are sometimes combined in the same window to take advantage of their different properties.

Complex cross-sectional profiles for frames and sashes, sophisticated glazing, gaskets, weatherstripping, and hardware are required to satisfy more-demanding performance requirements for windows. Consequently, contemporary windows are almost always shop fabricated, and, in some cases, they are shipped preglazed to the construction site. This means that the only operation required at the site is to secure them in the opening and seal the joints between the window and the wall opening.

Due to the sophisticated fabrication process for windows and the rigorous performance testing to which they are subjected, the architect's design of contemporary windows is generally limited to establishing their size, shape, and relationship with the building facade and selecting the manufacturers and window material that will satisfy the performance and aesthetic requirements. The detailing of windows is limited to designing their surrounds, that is, detailing at the jambs, head, and sill.

This chapter begins with an introduction to the commonly used window styles, materials used in window and sash frames, performance ratings of windows, and window installation.

A similar discussion of door types follows. Because of their immense variety, this chapter focuses on the more commonly used door types (interior wood and steel doors). The fire rating of windows and doors is discussed next, and the chapter concludes with a presentation of frequently used window and door terminology. The reader may choose to browse through the terminology before reading the main text.

31.1 WINDOW STYLES

Figure 31.1 shows various commonly used window styles that are classified into two broad categories:

- Fixed windows
- Operable windows

Fixed windows are the simplest of all windows. Because they do not have (operable) sashes, they are more economical and less likely to leak air or water. They are commonly used in nonresidential buildings with highly controlled heating, cooling, and ventilating systems. A fixed window is also referred to as a *direct-glaze window*. The term *picture window* is used for a fixed window whose width is larger than its height to provide a panoramic view.

Operable windows are commonly used in residential occupancies (homes, apartments, and hotels), sometimes in patient rooms of a hospital, and so on. In many situations, fixed and operable units are combined in the same window.

NOTE

Window Terminology

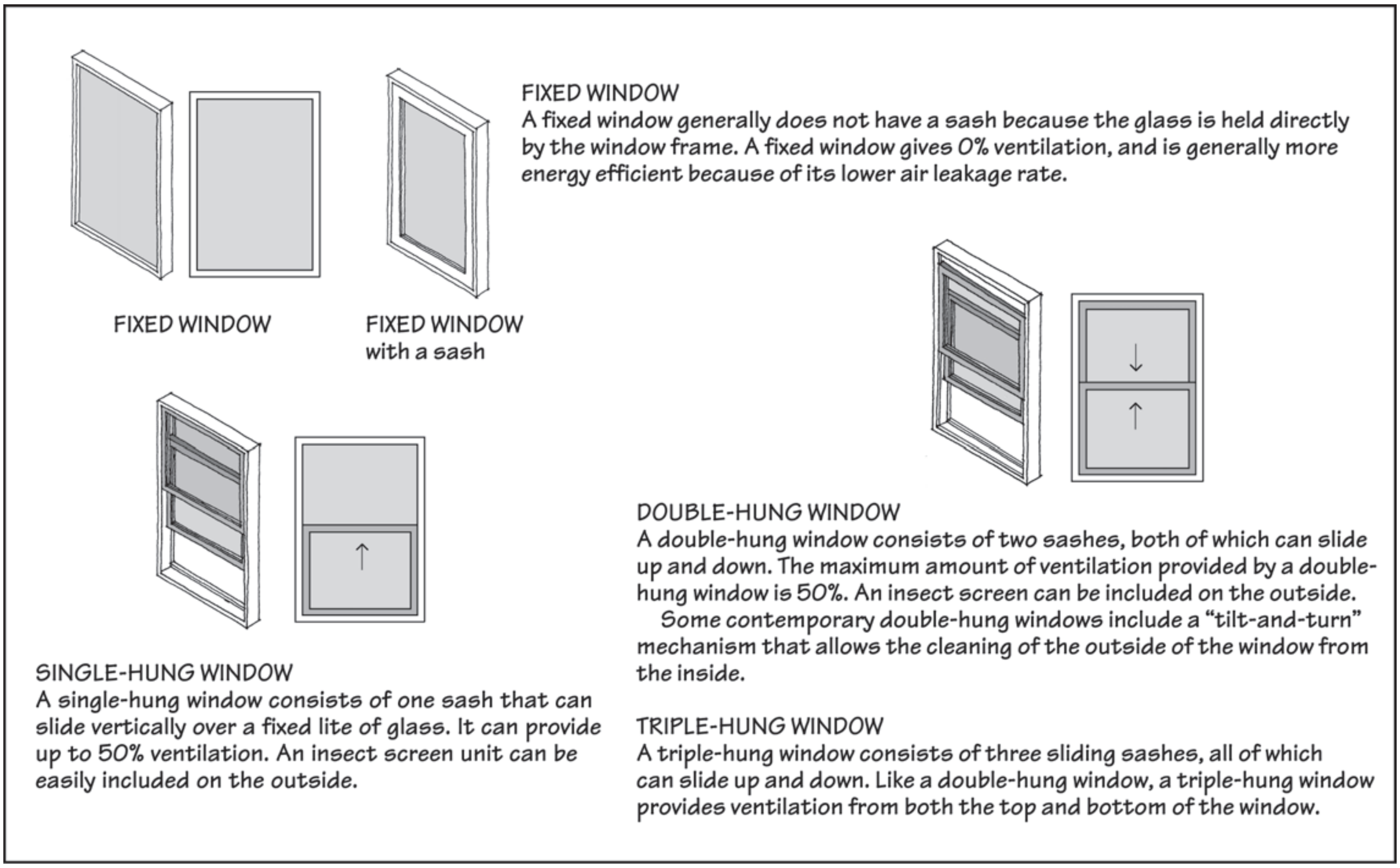
The reader may wish to brush up on the window terminology given at the end of the chapter before proceeding with this section.

31.2 WINDOW MATERIALS

As stated previously, five materials are used in contemporary windows: wood, aluminum, steel, vinyl, and fiberglass. The strengths and weaknesses of these materials are discussed in this section.

WOOD

Wood is the oldest material used for window frames and sashes. However, because of its swelling and shrinkage problems, fungal decay, and termite vulnerability, as well as the need



A fixed window generally does not have a sash because the glass is held directly by the window frame. A fixed window gives 0% ventilation, and is generally more energy efficient because of its lower air leakage rate.

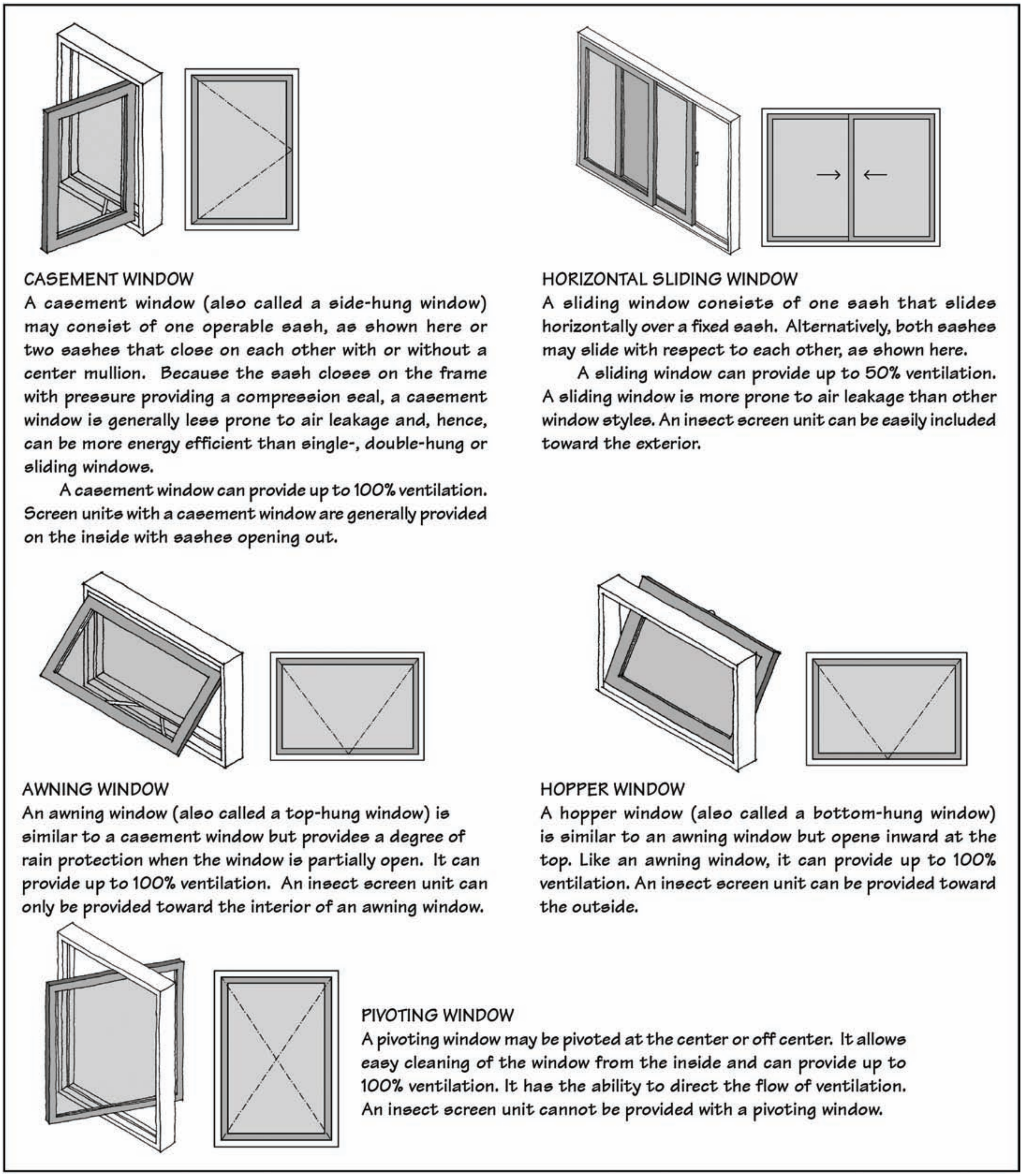
A double-hung window consists of two sashes, both of which can slide up and down. The maximum amount of ventilation provided by a double-hung window is 50%. An insect screen can be included on the outside.

Some contemporary double-hung windows include a "tilt-and-turn" mechanism that allows the cleaning of the outside of the window from the inside.

A single-hung window consists of one sash that can slide vertically over a fixed lite of glass. It can provide up to 50% ventilation. An insect screen unit can be easily included on the outside.

A triple-hung window consists of three sliding sashes, all of which can slide up and down. Like a double-hung window, a triple-hung window provides ventilation from both the top and bottom of the window.

FIGURE 31.1 Commonly used window styles.



CASEMENT WINDOW

A casement window (also called a side-hung window) may consist of one operable sash, as shown here or two sashes that close on each other with or without a center mullion. Because the sash closes on the frame with pressure providing a compression seal, a casement window is generally less prone to air leakage and, hence, can be more energy efficient than single-, double-hung or sliding windows.

A casement window can provide up to 100% ventilation. Screen units with a casement window are generally provided on the inside with sashes opening out.

HORIZONTAL SLIDING WINDOW

A sliding window consists of one sash that slides horizontally over a fixed sash. Alternatively, both sashes may slide with respect to each other, as shown here.

A sliding window can provide up to 50% ventilation. A sliding window is more prone to air leakage than other window styles. An insect screen unit can be easily included toward the exterior.

AWNING WINDOW

An awning window (also called a top-hung window) is similar to a casement window but provides a degree of rain protection when the window is partially open. It can provide up to 100% ventilation. An insect screen unit can only be provided toward the interior of an awning window.

HOPPER WINDOW

A hopper window (also called a bottom-hung window) is similar to an awning window but opens inward at the top. Like an awning window, it can provide up to 100% ventilation. An insect screen unit can be provided toward the outside.

PIVOTING WINDOW

A pivoting window may be pivoted at the center or off center. It allows easy cleaning of the window from the inside and can provide up to 100% ventilation. It has the ability to direct the flow of ventilation. An insect screen unit cannot be provided with a pivoting window.

FIGURE 31.1 ***(Continued)*** Commonly used window styles.

for periodic staining or painting, all-wood windows are not often used today. The advantage of wood is its high R-value. Additionally, its warmth and beauty are unmatched by any other window material. Therefore, wood windows are generally used in high-end homes and offices requiring cozy and homey interiors.

To improve their durability and eliminate the need for periodic painting, manufacturers provide wood windows whose frames and sashes are clad on the exterior with vinyl or aluminum. Unclad wood windows are generally used in historic buildings where restoration of their original design is required.

ALUMINUM

Aluminum is by far the most commonly used window material today. It is the only window material that is also used in glass curtain walls and storefronts. It is not subject to moisture shrinkage or swelling. Because the anodized or painted finish on aluminum is virtually permanent, aluminum windows require almost no maintenance.

The malleability and flexibility of aluminum are perhaps the most important reasons for its extensive use as a window and curtain wall material. Because of its malleability, aluminum can be extruded into complex cross sections, which are specially designed to facilitate the joinery of window and curtain wall components (see Principles in Practice at the end of this chapter). For example, continuous round, hollow intrusions, referred to as *screw splines*, are commonly provided in aluminum cross sections to join horizontal and vertical frame members, Figure 31.3.

The flexibility of aluminum allows the use of *snap-on* joinery, whereby two separate aluminum sections can be joined together without any fasteners. For example, in aluminum windows and curtain walls, glazing stops are simply snapped on (no need for screws or other fastening material; Figure 31.2). Additionally, two aluminum windows are routinely

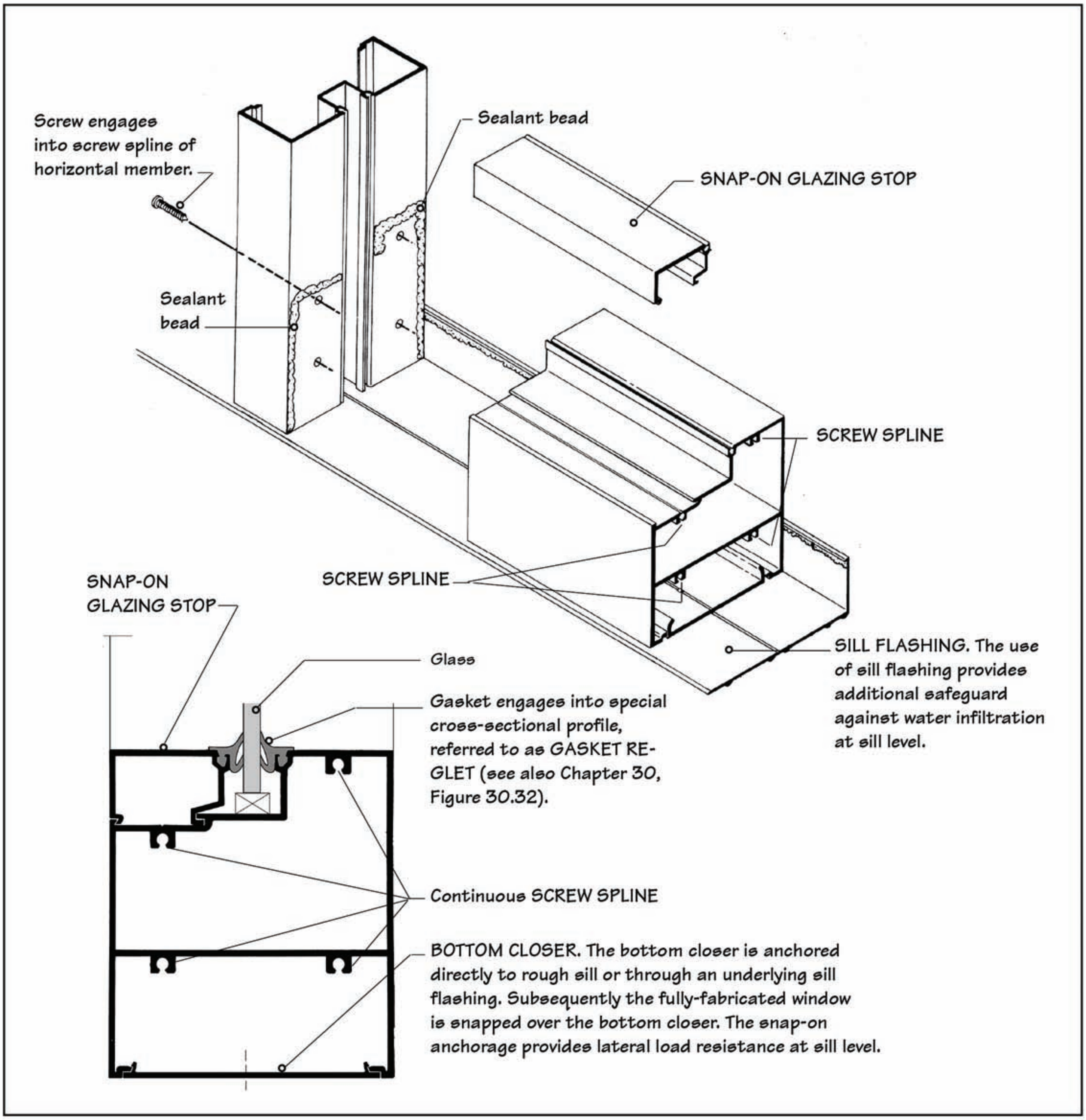

Screw engages into screw spline of horizontal member.
Sealant bead
SNAP-ON GLAZING STOP
Sealant bead
SCREW SPLINE
SNAP-ON GLAZING STOP
SCREW SPLINE
SILL FLASHING. The use of sill flashing provides additional safeguard against water infiltration at sill level.
Glass
Gasket engages into special cross-sectional profile, referred to as GASKET REGLET (see also Chapter 30, Figure 30.32).
Continuous SCREW SPLINE
BOTTOM CLOSER. The bottom closer is anchored directly to rough sill or through an underlying sill flashing. Subsequently the fully-fabricated window is snapped over the bottom closer. The snap-on anchorage provides lateral load resistance at sill level.

FIGURE 31.2 The cross-sectional profile of a typical aluminum window or curtain wall frame member looks complex, but each intrusion or protrusion has a special purpose. Observe the use of screw splines to connect horizontal and vertical frame members and snap-on cross-sectional profiles that allow members to be connected together without any fasteners.

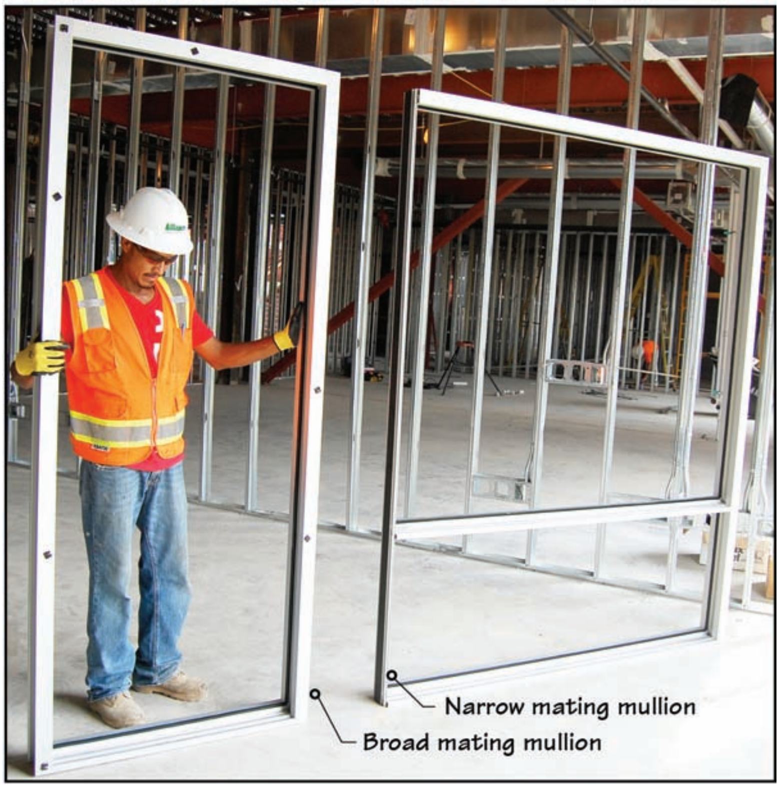


FIGURE 31.3 Two separate aluminum window frames ready to be snapped together at mating mullions to form one window assembly. The right-hand frame has a narrow mating mullion while the left-hand frame has a broad mating mullion so that the overall width of the two mullions when snapped together is the same as that of the two end mullions.

snap-connected by using mating mullion profiles to provide a larger window with a common mullion—without the use of fasteners, Figures 31.3 and 31.4.

The disadvantage of aluminum is its low R-value. However, with the introduction of *thermally improved*—also called *thermally broken* (see Figure 30.23)—aluminum frames, the situation has substantially improved.

STEEL

Before the introduction of aluminum for windows, steel was commonly used as an alternative to wood. Steel corrosion and the need for frequent painting have substantially reduced the use of steel windows. However, because steel is a strong material, the frame members

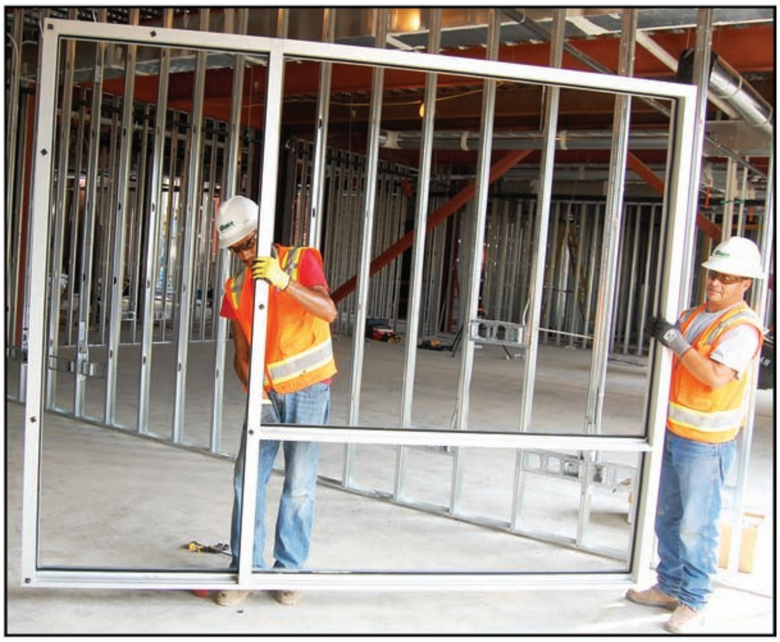


FIGURE 31.4 The two window frames of Figure 31.3 have been snapped together to form one window assembly without the use of fasteners. The assembly is being carried for installation in wall opening.

can be narrower than those of other materials, giving a sleeker window appearance. Because of steel's strength, steel windows are often specified for prisons and other locations where greater durability and greater resistance to lateral loads (e.g., blast-resistant glazing) are required. Steel windows are also used in the renovation work of historic buildings.

Vinyl and Fiberglass

Vinyl (an abbreviation for polyvinyl chloride, PVC) frames and sashes are almost maintenance free because vinyl does not corrode or degrade due to fungal or termite attack. Vinyl windows require no painting and are available in a variety of nonfading colors. Vinyl frame and sash cross sections are made by the extrusion process and are generally hollow, Figure 31.5. They provide an excellent R-value.

A major disadvantage of vinyl, and of plastics in general, is their high coefficient of thermal expansion. The introduction of fiberglass in windows has substantially reduced this problem. The coefficient of thermal expansion of fiberglass is compatible with that of glass. Thus, fiberglass frames and sashes are dimensionally stable, strong, and available in different colors.

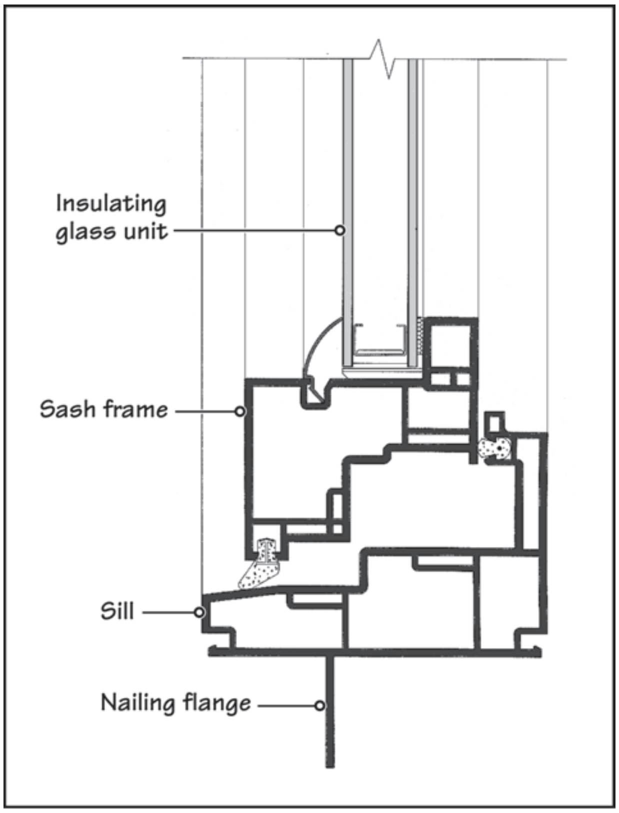


FIGURE 31.5 Typical cross-sectional profile of a vinyl window.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The term *direct-glaze window* implies
   - **a.** an operable window.
   - **b.** a fixed window.
   - **c.** a fixed window whose length is greater than its height.
   - **d.** a fixed window whose height is greater than its length.
   - **e.** none of the above.
2. The term *picture window* implies
   - **a.** an operable window.
   - **b.** a fixed window.
   - **c.** a fixed window whose length is greater than its height.
   - **d.** a fixed window whose height is greater than its length.
   - **e.** none of the above.
3. Which of the following window types can provide up to 100% ventilation when fully open?
   - **a.** Single-hung window
   - **b.** Double-hung window
   - **c.** Sliding window
   - **d.** Casement window
   - **e.** All of the above
4. Which of the following windows is top-hung?
   - **a.** Awning window
   - **b.** Hopper window
   - **c.** Casement window
   - **d.** Pivoting window
   - **e.** None of the above
5. In vinyl- (or aluminum-) clad windows, the cladding is used on exterior
   - **a.** window frame members.
   - **b.** sash frame members.
   - **c.** both window frame and sash frame members.
6. Screw splines are provided in
   - **a.** window and curtain wall frames made from wood.
   - **b.** window and curtain wall frames made from steel.
   - **c.** window and curtain wall frames made from vinyl.
   - **d.** window and curtain wall frames made from aluminum.
   - **e.** all of the above.

(*Continued*)

PRACTICE **QUIZ** *(Continued)*

7. Screw splines are round, hollow intrusions in frame members that facilitate the connection of horizontal and vertical members of a(n)
- **a.** wood window.
- **b.** aluminum window.
- **c.** steel window.
- **d.** vinyl window.
- **e.** all of the above.

8. Snap-on joinery is generally used in
- **a.** wood windows.
- **b.** aluminum windows.
- **c.** steel windows.
- **d.** all of the above.
- **e.** none of the above.

31.3 PERFORMANCE RATINGS OF WINDOWS

Apart from aesthetic considerations such as shape, style, frame color, and finish, several performance characteristics must be considered in selecting a window for a project. Two rating systems, one relating to a window's energy performance and the other relating to a window's structural and water-leakage performance, help architects in this task. Both systems are material neutral—that is, they apply uniformly to windows made of different materials. Additionally, they apply to the entire window assembly, consisting of the frame, sash, glass, gaskets, and so on.

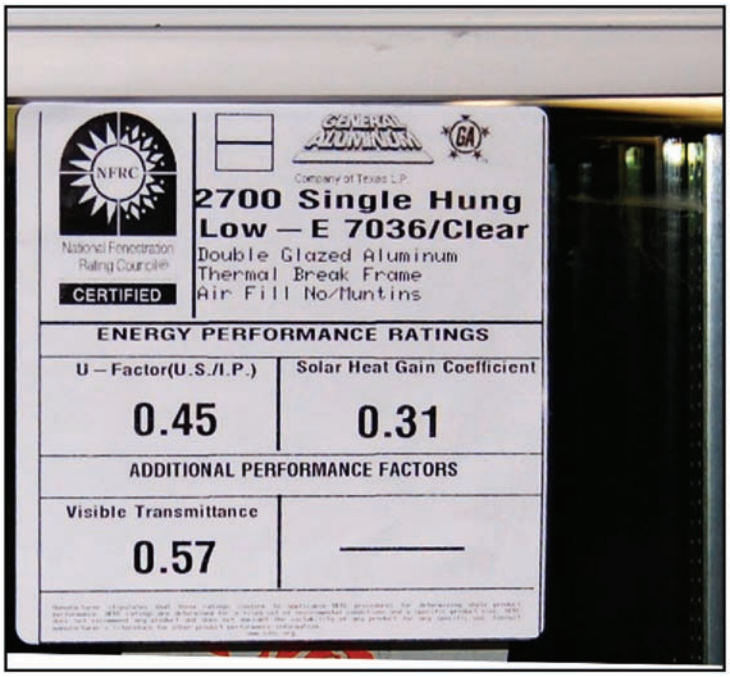
ENERGY-PERFORMANCE RATING OF A WINDOW

The energy-performance rating of a window assembly is provided by the National Fenestration Rating Council (NFRC), which is backed by the U.S. government's Energy Star initiative. NFRC-rated windows are required to be labeled for their U-values, solar heat gain coefficient (SHGC), and visible transmittance (VT), Figure 31.6. Labeling for other energy performance criteria, such as air leakage rate and the condensation resistance factor (CRF) is at the discretion of the manufacturer.

STRUCTURAL, WATER-LEAKAGE, AND OTHER PERFORMANCE RATINGS OF A WINDOW

In addition to being energy efficient, a window assembly must be strong enough to resist wind loads, it should not leak water or air, and the window's locking mechanism should prevent forced entry. The window manufacturing industry (comprising the manufacturers of wood, aluminum, vinyl, and fiberglass windows) has jointly established standards by which their windows are tested. All windows must be tested for

- Resistance to wind loads
- Resistance to water leakage
- Resistance to air leakage
- Resistance to forced entry



2700 Single Hung
Low — E 7036/Clear
Double Glazed Aluminum
Thermal Break Frame
Air Fill No/Muntins

ENERGY PERFORMANCE RATINGS

U – Factor(U.S./I.P.)	Solar Heat Gain Coefficient
0.45	0.31

ADDITIONAL PERFORMANCE FACTORS

Visible Transmittance	
0.57	———

FIGURE 31.6 A typical label on an NFRC-rated window. The National Fenestration Rating Council (NFRC) requires the declaration by the manufacturer of the window's U-value, solar heat gain coefficient (SHGC), and visible transmittance (VT), which are 0.45, 0.31, and 0.57, respectively for this window.

Based on the test results, a window is assigned a rating designation that includes the following information:

- *Window style:* whether the window is a fixed, casement, sliding, or awning window. The acronyms for the commonly used window styles are given in Table 31.1.
- *Window performance class:* the five performance classes, coded as R, LC, C, HC, or AW, Table 31.2.
- *Window performance grade:* the allowable (or design) wind load on the window in psf (pounds per square foot). A factor of safety of 1.5 is used so that if the window assembly resists a wind load of 45 psf, its design wind load is 30 psf (i.e., the window's performance grade is 30).

  The window is also tested for water leakage under a static water pressure given in Table 31.2. Under this pressure, the assembly should not leak any water. Thus, water leakage is a pass/fail test. The window's air leakage should not exceed 0.3 cfm/ft^2 (cubic feet per minute per square foot)—another pass/fail test. The window should also pass the forced-entry resistance test as specified in the standard, once again a pass/fail test.
- *Window size:* an important part of the designation system. It is stated as "window width × window height" in inches. Generally, if everything else is the same, a smaller window generally performs better than a larger window under the tests. Therefore, the standard specifies a certain minimum window size for each performance class and performance grade. The manufacturer can exceed the specified size requirement, and if that is the case, it can be so included in the designation, as explained in Figure 31.7.

TABLE 31.1 ABBREVIATIONS FOR COMMONLY USED WINDOW STYLES IN THE WINDOW-RATING DESIGNATION

Window style	Code
Fixed	F
Single/double/triple hung	H
Casement	C
Horizontal sliding	HS
Awning/hopper	AP
Vertically pivoted	VP
Horizontally pivoted	HP

Other Performance Characteristics of Windows

The four performance characteristics just described are the minimum requirements for windows. Generally, a manufacturer will have its windows tested for several other characteristics, such as the operating force test (force required to open and close windows), life-cycle test (which determines the damage over time to hardware parts used in the window), and the vertical deflection test (which determines the deflection of a sash in a casement window). Acoustical windows are tested for their sound insulation property.

Windows and Building Codes

Windows in habitable rooms of dwelling units must satisfy the building code's requirement for a certain minimum amount of natural light and ventilation. They are also required to provide a means of emergency egress from the dwelling in the event of fire. For example,

NOTE

Building Fenestration and the International Energy Conservation Code

The International Energy Conservation Code (IECC) places restrictions on various energy-related properties of building fenestration (glazed and unglazed doors, windows, and skylights). For example, the 2015 IECC requires that the U-value of fixed vertical fenestration in commercial buildings in climate zones 1 and 2 not exceed 0.50, which is equal to a minimum R-value of 2.0. The maximum U-values decrease with increasing climate zone number (cooler climates). Thus, for climate zone 6, the corresponding maximum U-value is 0.36, equivalent to a minimum R-value of approximately 3.0.

The fenestration leakage rate is limited to 0.3 cfm/ft^2 for all climate zones. The maximum values of SHGC is also regulated and is a function of the climate zone (see Chapter 30).

Note that the preceding information applies to compliance with the prescriptive provisions of the IECC. If whole building energy performance modeling is used, the designer has the freedom to trade off between various factors that affect energy use in buildings.

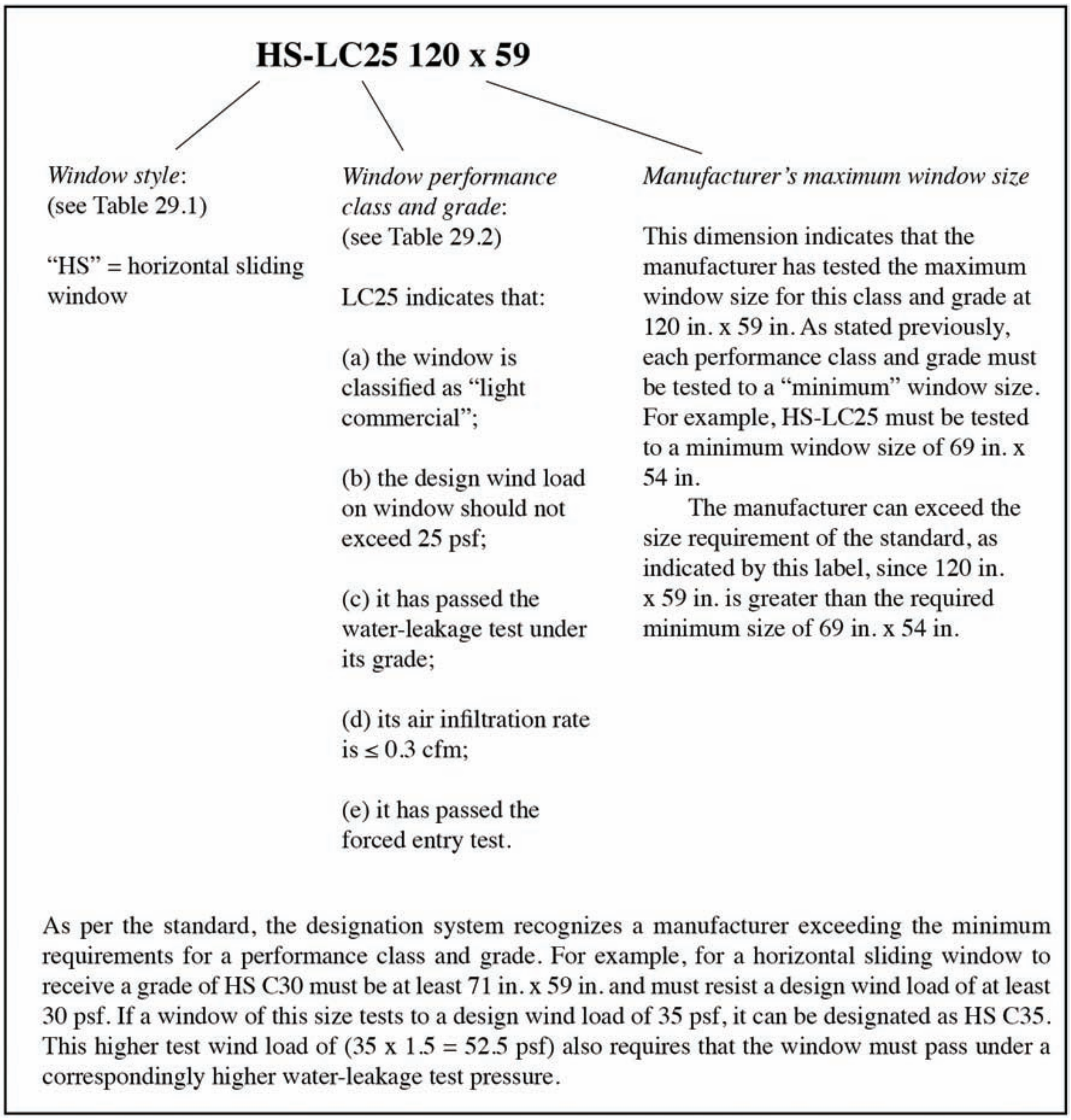
TABLE 31.2 PERFORMANCE-CLASS AND PERFORMANCE-GRADE REQUIREMENTS OF WINDOWS

Performance class and abbreviation	Performance grade (design wind load) (psf)	Minimum wind load resistance (psf)*	Water-leakage test pressure (psf)†	Air-leakage test pressure (psf)	Air-leakage rate ft^3/(min. ft^2)
Residential (R)	15	22.5	2.86	1.57	0.3
Light commercial (LC)	25	37.5	3.75	1.57	0.3
Commercial (C)	30	45.0	4.50	1.57	0.3
Heavy commercial (HC)	40	60.0	6.00	1.57	0.3
Architectural (AW)	40	60.0	8.00	6.24	0.3

*The design wind load equals two-thirds of the load that a window resists under the test. For example, if the window resists 60 psf under the test, the design wind load for the window is 40 psf. In other words, the window may be subjected to a maximum wind load of 40 psf in service. Hence, the window's performance grade is 40.

†The water leakage of a window is determined by subjecting it to a static pressure that is 15% of its design wind load. Thus, if the design wind load for a window is 40 psf, it must pass a water-leakage test under a pressure of 6.0 psf. AW windows are tested under a pressure that is 20% of the design wind load (in place of 15%), and R windows are tested under 19% of design wind-load pressure.

Observe that HC and AW windows have the same performance grade of 40, but AW windows must resist water leakage and air leakage under higher pressures.



HS-LC25 120 x 59

Window style:
(see Table 29.1)

"HS" = horizontal sliding window

Window performance class and grade:
(see Table 29.2)

LC25 indicates that:

(a) the window is classified as "light commercial";

(b) the design wind load on window should not exceed 25 psf;

(c) it has passed the water-leakage test under its grade;

(d) its air infiltration rate is ≤ 0.3 cfm;

(e) it has passed the forced entry test.

Manufacturer's maximum window size

This dimension indicates that the manufacturer has tested the maximum window size for this class and grade at 120 in. x 59 in. As stated previously, each performance class and grade must be tested to a "minimum" window size. For example, HS-LC25 must be tested to a minimum window size of 69 in. x 54 in.

The manufacturer can exceed the size requirement of the standard, as indicated by this label, since 120 in. x 59 in. is greater than the required minimum size of 69 in. x 54 in.

As per the standard, the designation system recognizes a manufacturer exceeding the minimum requirements for a performance class and grade. For example, for a horizontal sliding window to receive a grade of HS C30 must be at least 71 in. x 59 in. and must resist a design wind load of at least 30 psf. If a window of this size tests to a design wind load of 35 psf, it can be designated as HS C35. This higher test wind load of (35 x 1.5 = 52.5 psf) also requires that the window must pass under a correspondingly higher water-leakage test pressure.

FIGURE 31.7 Explanation of a typical label on a window tested under AAMA/WDMA/CSA 101/I.S.2/A440.

building codes generally require the clear area of at least one window in each sleeping room of a dwelling, when open, to be at least 5.7 sq ft.

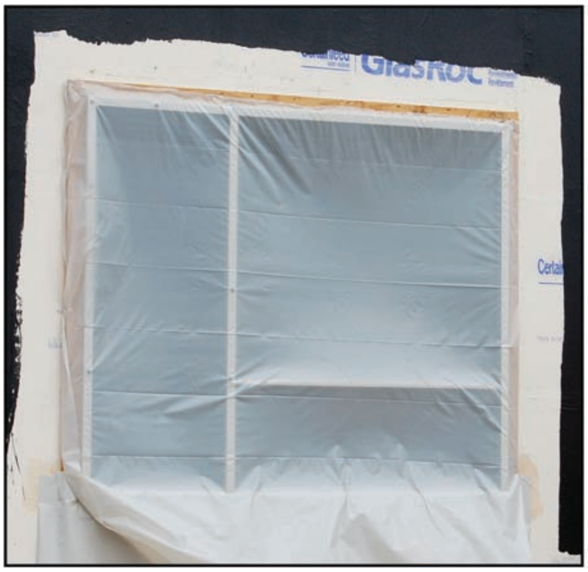


FIGURE 31.8 In most buildings, the windows are installed before constructing the exterior cladding. Therefore, they are protected from damage and disfigurement caused by the construction of cladding with a plastic sheet cover.

31.4 WINDOW INSTALLATION AND SURROUNDING DETAILS

Contemporary windows are generally brought to the site fully assembled and glazed, which simplifies the installation process. On-site glazing is generally limited to fixed windows with large glass panes.

A window may be installed before or after the exterior wall cladding is in place. Most commercial window manufacturers recommend the installation of their windows after the exterior wall cladding is in place to prevent physical damage to windows, such as breakage of glass and scratching of coatings. Chemical damage is also a concern. For example, fresh mortar can adversely react with aluminum. If window installation must precede the exterior wall finish, adequate precautions must be taken to protect the windows from damage, Figure 31.8.

INSTALLATION OF WINDOWS WITH NAILING FLANGES

Windows in most residential (both low-rise and high-rise) buildings are factory-glazed, which eliminates field glazing, thus reducing cost and time. Additionally, they are provided with a nailing flange all around their perimeter, Figure 31.9. A nailing flange is an integral part of the window frame and projects over the rough opening so that the installation of window involves only the fastening of nailing flanges to the opening frame from the outside.

Because the flanges project over the entire window perimeter, they seal the rough opening, providing a built-in flashing. However, additional waterproofing of the rough opening is generally recommended to provide a second line of defense against water and air leakage, Figure 31.10.

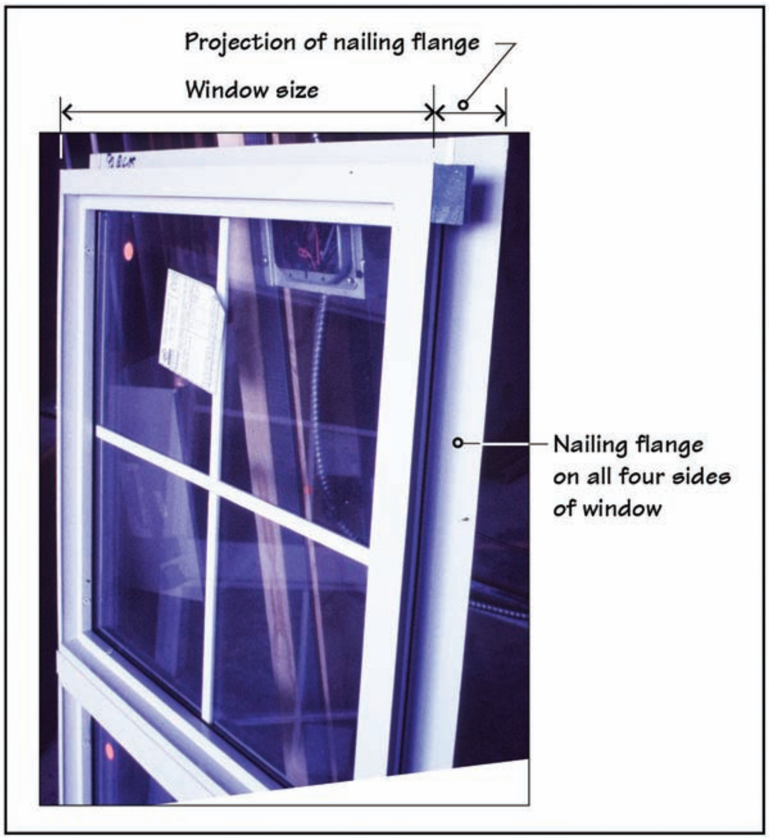
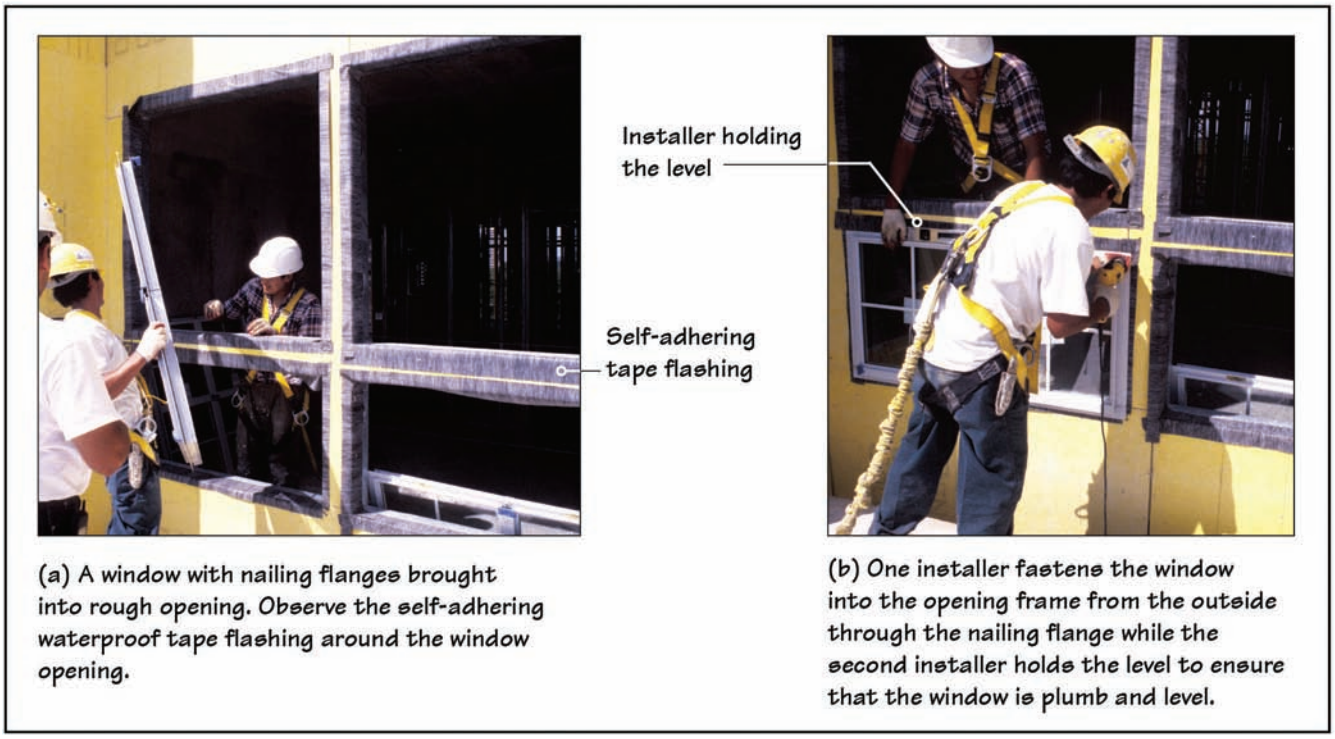

Projection of nailing flange
Window size
Nailing flange on all four sides of window

FIGURE 31.9 Most factory-glazed, residential windows are provided with nailing flanges, which makes their installation into window's rough opening faster and easier.


Installer holding the level
Self-adhering tape flashing

(a) A window with nailing flanges brought into rough opening. Observe the self-adhering waterproof tape flashing around the window opening.

(b) One installer fastens the window into the opening frame from the outside through the nailing flange while the second installer holds the level to ensure that the window is plumb and level.

FIGURE 31.10 Installation of a factory-glazed window through nailing flanges.

INSTALLATION OF WINDOWS WITHOUT NAILING FLANGES

Windows without nailing flanges can be installed in several ways. Two commonly used methods for aluminum windows are shown in Figures 31.11 and 31.12. Figure 31.11 shows the use of a perimeter receptor frame comprising a sill receptor (also called a *subsill*), two jamb receptors, and a head receptor. The receptors are first anchored to the rough opening with anchorage points fully sealed. Subsequently, the window (complete with frame, sashes, glass, hardware, etc.) is placed within the receptor frame.

Lateral load resistance to the window is provided by aluminum retainer clips that are snapped onto the receptors from the inside. If their thickness, cross-sectional profile, and locking striations are changed, retainer clips can provide the required lateral load resistance.

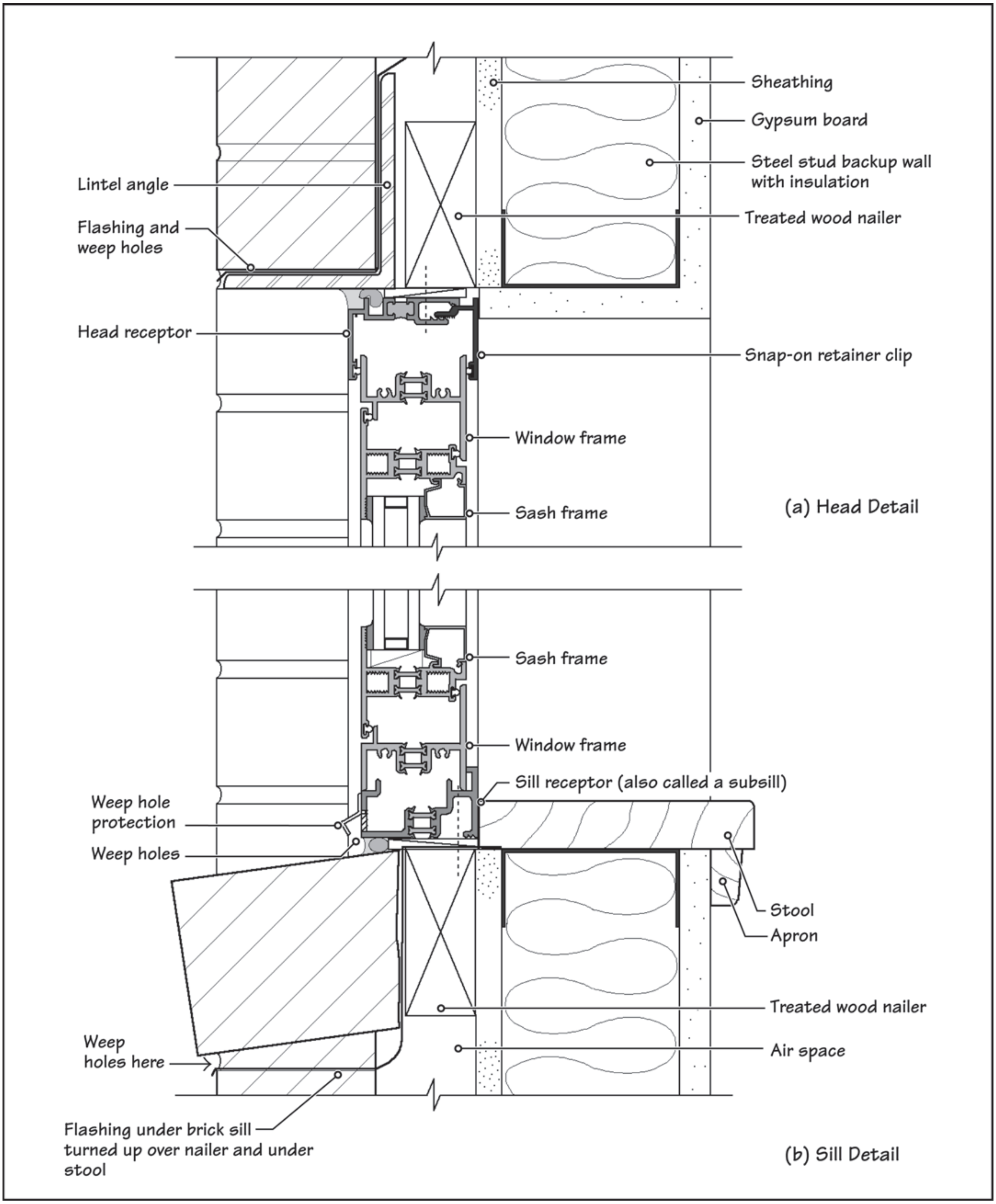

Sheathing
Gypsum board
Steel stud backup wall with insulation
Lintel angle
Flashing and weep holes
Treated wood nailer
Head receptor
Snap-on retainer clip
Window frame
Sash frame
(a) Head Detail
Sash frame
Window frame
Sill receptor (also called a subsill)
Weep hole protection
Weep holes
Stool
Apron
Treated wood nailer
Air space
Weep holes here
Flashing under brick sill turned up over nailer and under stool
(b) Sill Detail

FIGURE 31.11 A preglazed aluminum window anchored to a steel stud–backed brick veneer wall using receptors and retainer clips.

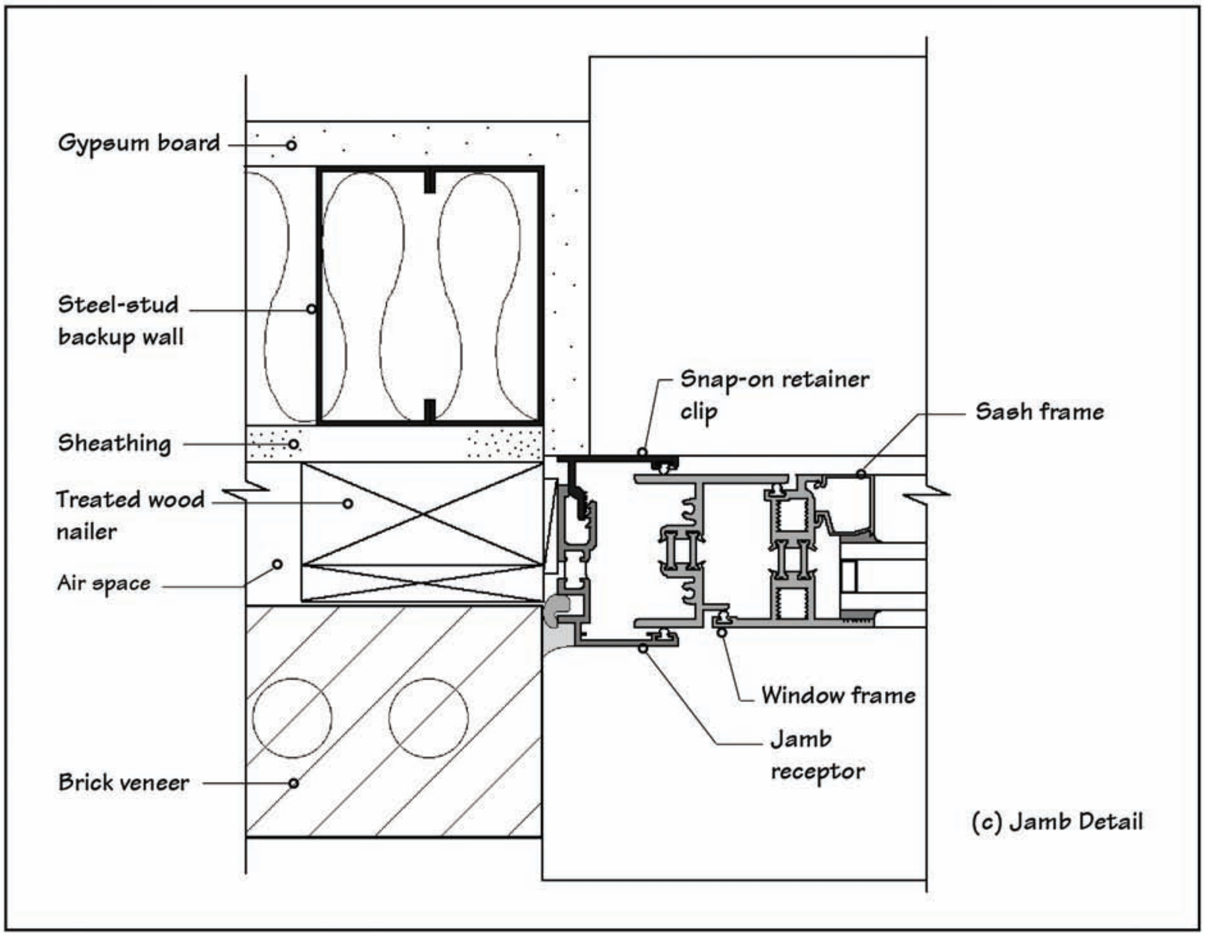


FIGURE 31.11 (*Continued*) A preglazed aluminum window anchored to a steel stud–backed brick veneer wall using receptors and retainer clips.

Interior finishes around the jambs, sill, and head are now installed. In this method of installation, the window is not directly anchored to the rough opening.

Any incidental water that leaks into the window is collected in the subsill. Therefore, the subsill is provided with end dams to prevent its runoff from the ends and also with weep holes to let the water drain out.

Figure 31.12 shows an alternative anchorage method, which utilizes two-piece interior perimeter trims. In this method, the window is first placed in the opening, squared, and leveled. The first (L-shaped) trim piece is then anchored to the rough opening on all four sides and also to the window. Subsequently, the second trim piece is snapped on the first trim piece. Interior finishes can then be applied to the opening.

The details shown in Figures 31.11 and 31.12 can be modified in several ways, depending on the wall construction and the exterior finish. Manufacturers have several standard components for use with different interior and exterior requirements. They can also provide custom-made trims and accessories at little or no additional cost.

31.5 CLASSIFICATION OF DOORS

Because of the large variety of doors used in contemporary buildings, they can be classified in several ways. The simplest classification is to group them as *interior* and *exterior doors*. Exterior doors include entry doors and garage and overhead doors. Entry doors in residential buildings are generally insulated and rated for energy performance.

CLASSIFICATION BASED ON DOOR MATERIAL

Doors can also be classified based on the materials of which they are made. Wood and metal (steel, stainless steel, and aluminum) are the commonly used door materials. Fiberglass-reinforced plastic (FRP) is a more recently introduced material.

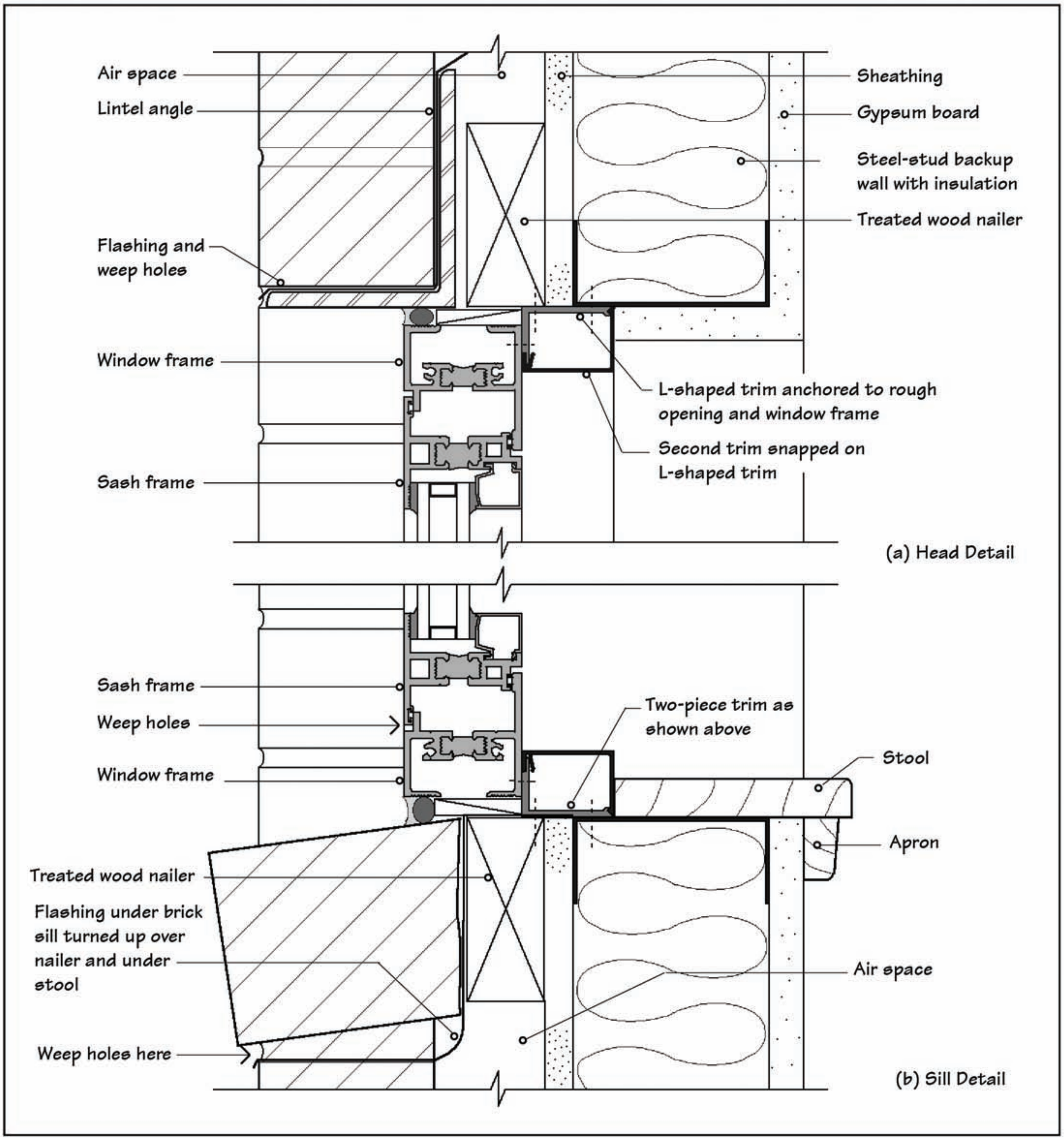

Air space
Lintel angle
Flashing and weep holes
Window frame
Sash frame
Sheathing
Gypsum board
Steel-stud backup wall with insulation
Treated wood nailer
L-shaped trim anchored to rough opening and window frame
Second trim snapped on L-shaped trim
(a) Head Detail
Sash frame
Weep holes
Window frame
Treated wood nailer
Flashing under brick sill turned up over nailer and under stool
Weep holes here
Two-piece trim as shown above
Stool
Apron
Air space
(b) Sill Detail

FIGURE 31.12 A preglazed aluminum window anchored using two-piece trims.

Wood doors are the most popular interior doors. Among the metal doors, steel doors are used where greater security, fire resistance, rot resistance, blast resistance, and wind-load resistance are required. Stainless steel doors are preferred for food-processing plants, freezer rooms, commercial kitchens, and so on. (Note: steel doors are commonly made from sheet steel and are generally referred to as *hollow metal doors*.)

Aluminum doors are generally glazed and are commonly used in public buildings. Aluminum flush doors and panel doors are specified where corrosion resistance is important, such as in water-treatment plants, swimming pools, and pumping stations.

CLASSIFICATIONS BASED ON DOOR OPERATION AND DOOR STYLES

A helpful classification of doors is based on their mode of operation, as shown in Figure 31.13. Of these, the single-leaf hinged door is most commonly used. Another classification is based on door style (i.e., door elevation), Figure 31.14.

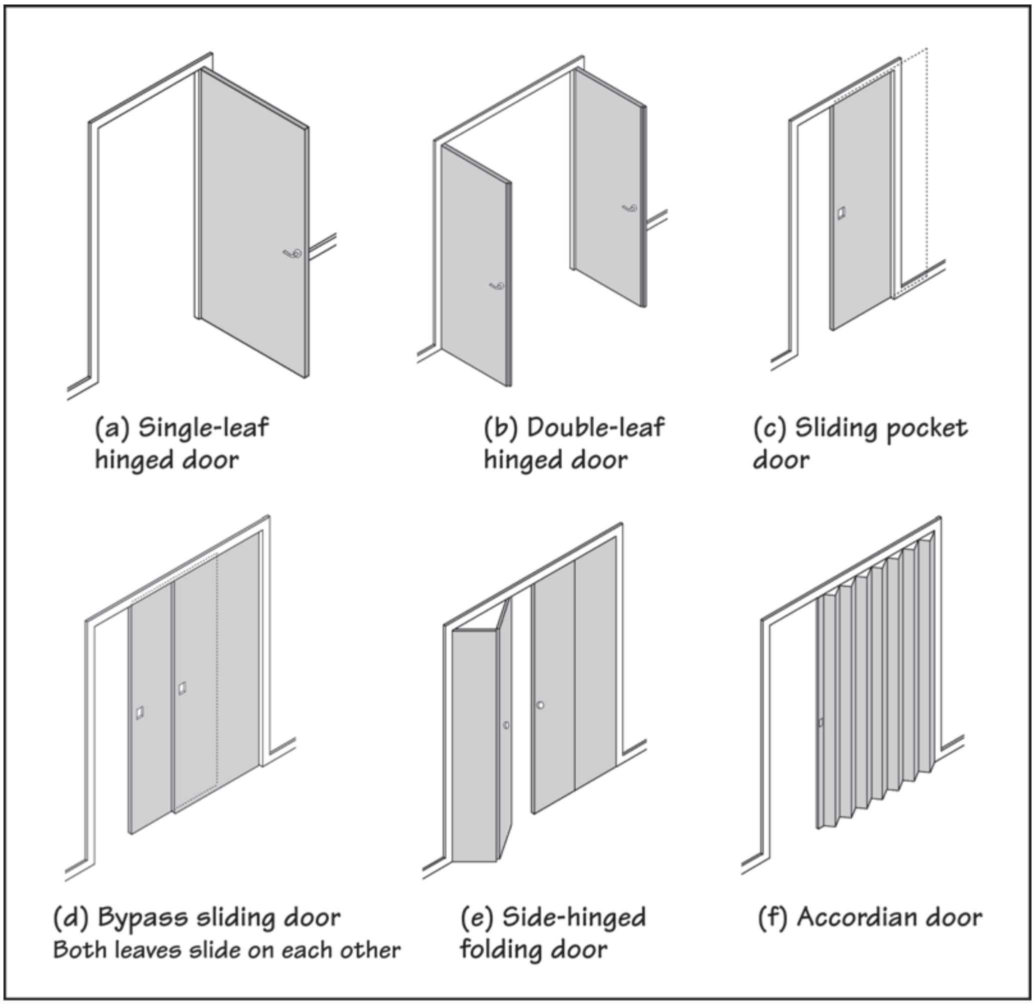

(a) Single-leaf hinged door
(b) Double-leaf hinged door
(c) Sliding pocket door
(d) Bypass sliding door
Both leaves slide on each other
(e) Side-hinged folding door
(f) Accordian door

FIGURE 31.13 Classification of doors based on their mode of operation.

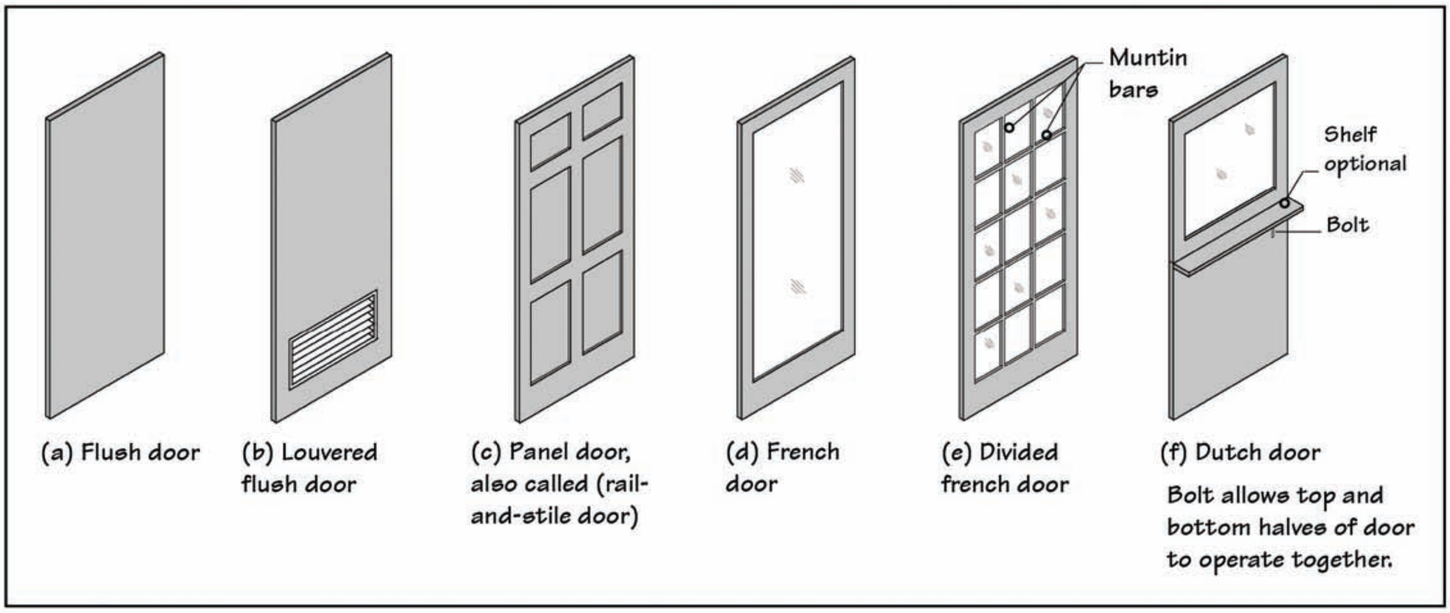
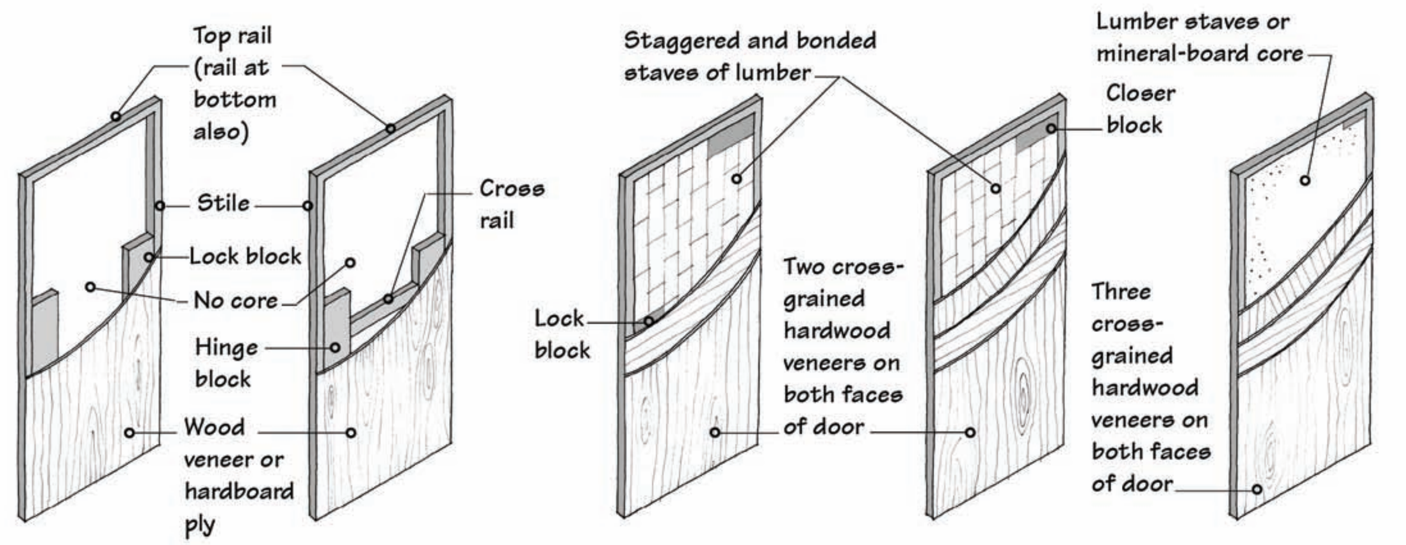

Muntin bars
Shelf optional
Bolt
(a) Flush door
(b) Louvered flush door
(c) Panel door, also called (rail-and-stile door)
(d) French door
(e) Divided french door
(f) Dutch door
Bolt allows top and bottom halves of door to operate together.

FIGURE 31.14 Common wood door styles.

Of the various styles shown in Figure 31.14, flush doors and panel doors are most popular. Construction details of wood flush doors and panel doors are illustrated in Figures 31.15 and 31.16, respectively. Figure 31.17 gives standard door sizes for wood doors, their hardware, and their hand conventions.

Metal (steel) doors are generally hollow-core doors and are available in both flush and panel door styles. The types and construction of metal hollow-core flush doors are illustrated in Figures 31.18 and 31.19, respectively.


Top rail (rail at bottom also)
Stile
Lock block
No core
Hinge block
Wood veneer or hardboard ply
Cross rail
Staggered and bonded staves of lumber
Lock block
Two cross-grained hardwood veneers on both faces of door
Lumber staves or mineral-board core
Closer block
Three cross-grained hardwood veneers on both faces of door

Standard hollow-core door

Hollow-core door with cross rail

(a) Hollow-core flush doors

5-ply solid-core flush door with glued lumber strips (staves)

7-ply solid-core flush door with glued lumber staves or mineral board (required for fire-rated doors)

(b) Solid-core flush doors with staved lumber core

WOOD FLUSH DOOR ANATOMY

Flush doors consist of:
(a) Face material
(b) Core

HOLLOW-CORE FLUSH DOORS

Face material is generally wood veneer or hardboard.
Core is usually hollow but can also be of honeycomb or cellular fiberboard.
Hollow-core flush doors are generally used in residential interiors.

SOLID-CORE FLUSH DOORS

Face material consists of hardwood veneers, high-density plastic laminate (HDPL) or sheet metal.
Core may consist of: (a) staved lumber (b) particle board, (c) mineral board, or (d) structural composite lumber

Solid core flush doors are more durable, secure, and provide greater sound insulation and fire resistance than hollow core flush doors. They are commonly used as interior doors in public buildings. The facing on staved lumber doors must be thick enough so that the staves do not telegraph through.

WOOD FLUSH DOOR GRADES

According to Architectural Woodworking Institute (AWI), wood flush doors are available in following grades.

- Premium
- Custom
- Economy

FIGURE 31.15 Anatomies of wood (hollow-core and solid-core) flush doors.

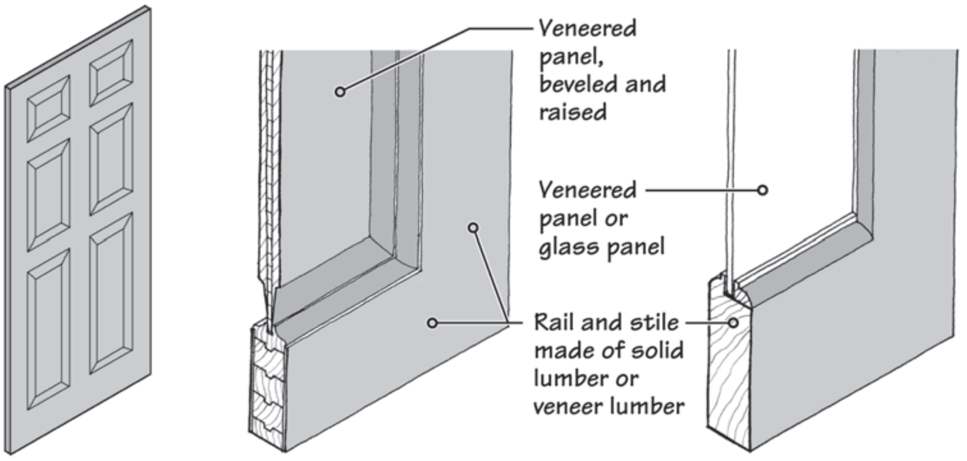
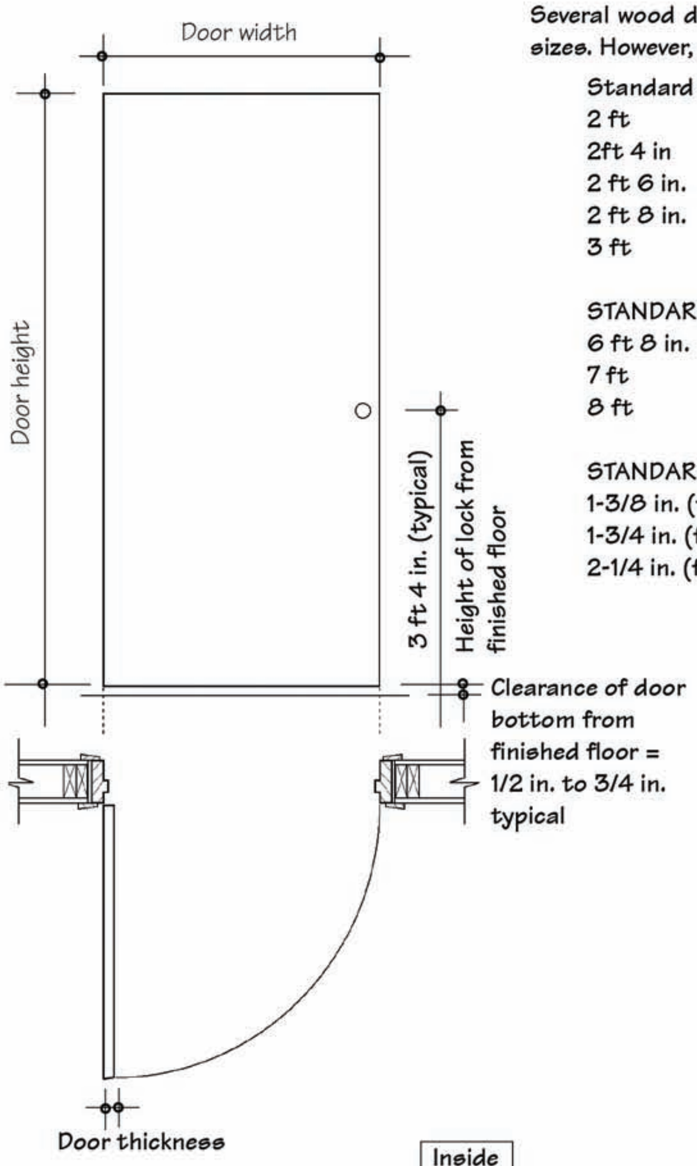

Veneered panel, beveled and raised
Veneered panel or glass panel
Rail and stile made of solid lumber or veneer lumber

FIGURE 31.16 Details of a typical wood panel door. Panel doors are also imitated using other materials.


Door width
Door height
3 ft 4 in. (typical)
Height of lock from finished floor
Clearance of door bottom from finished floor = 1/2 in. to 3/4 in. typical
Door thickness

STANDARD WOOD DOOR SIZES

Several wood door manufacturers fabricate doors to custom design and sizes. However, standard doors are more economical and commonly used.

Standard Door Widths
2 ft
2ft 4 in
2 ft 6 in.
2 ft 8 in.
3 ft

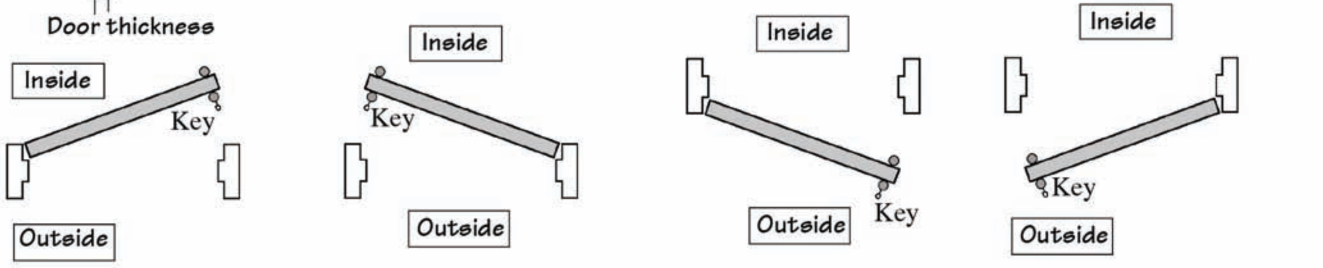
STANDARD DOOR HEIGHTS
6 ft 8 in.
7 ft
8 ft

STANDARD DOOR THICKNESS
1-3/8 in. (for hollow-core)
1-3/4 in. (for solid-core)
2-1/4 in. (for acoustical solid-core doors)

DOOR HARDWARE

Door hardware includes components that are required for the operation of the door:

(a) Hinges (generally three per door; a greater number and heavier hinges may be required for a heavy door)
(b) Lockset—locks, latches and bolts
(c) Push and pull bars
(d) Panic hardware (on exit doors)
(e) Closer
(f) Stop and holder
(g) Kick plate
(h) Threshold


Inside
Key
Outside
Inside
Key
Outside
Inside
Outside
Key
Inside
Key
Outside

LEFT-HAND (LH) DOOR

RIGHT-HAND (RH) DOOR

LEFT-HAND REVERSE (LHR) DOOR

RIGHT-HAND REVERSE (RHR) DOOR

DOOR HAND CONVENTION

Door hand conventions are used in specifying door hardware. To determine the hand of a door, face the outside of door. The outside of door is its "key side" or the side that would be secured if a lock were used. The hinge side of door determines the door's hand. The hand is referred to as "reverse", if the door swings toward the key side, that is, toward the outside.

FIGURE 31.17 Standard wood door sizes, hardware, and door hand conventions.

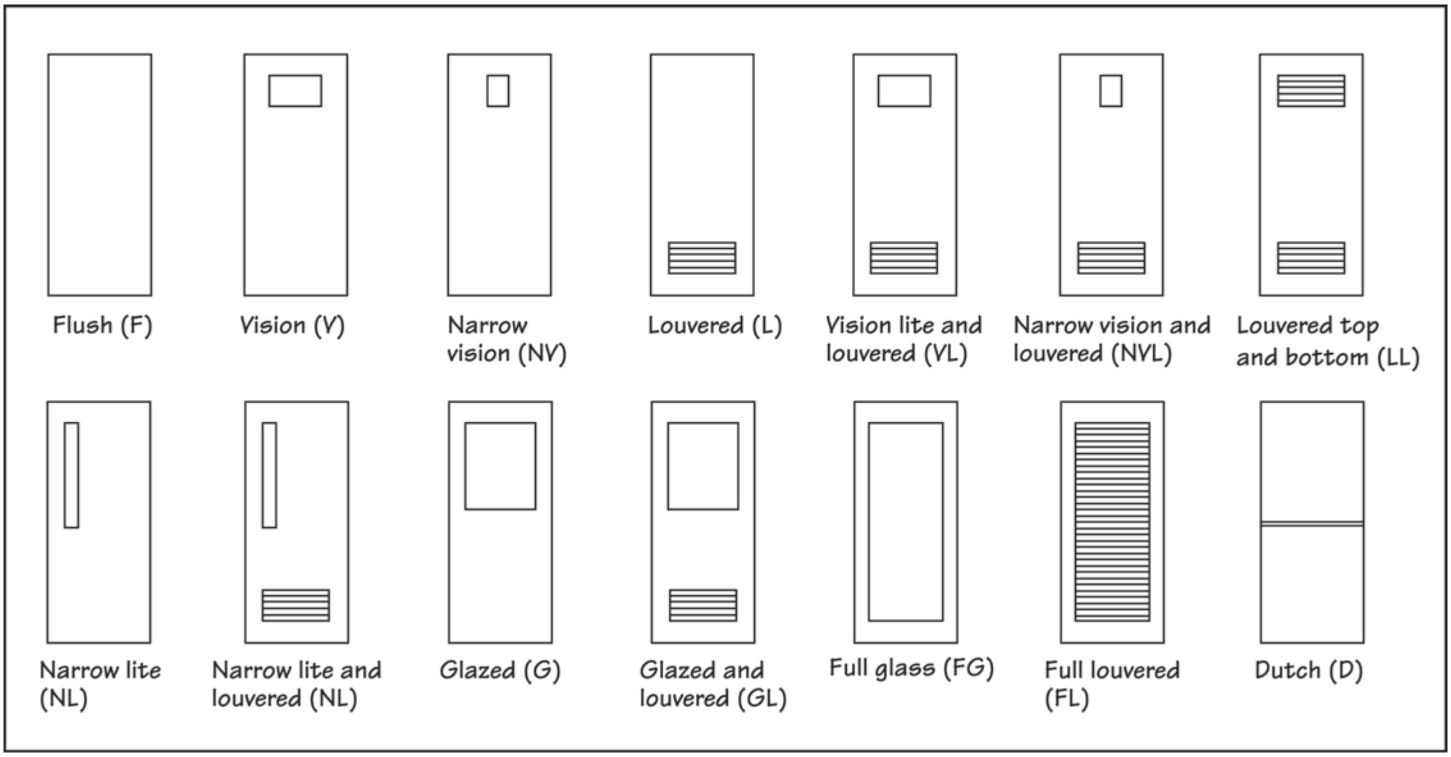

Flush (F)
Vision (V)
Narrow vision (NV)
Louvered (L)
Vision lite and louvered (VL)
Narrow vision and louvered (NVL)
Louvered top and bottom (LL)
Narrow lite (NL)
Narrow lite and louvered (NL)
Glazed (G)
Glazed and louvered (GL)
Full glass (FG)
Full louvered (FL)
Dutch (D)

FIGURE 31.18 Commonly used hollow metal flush door styles.

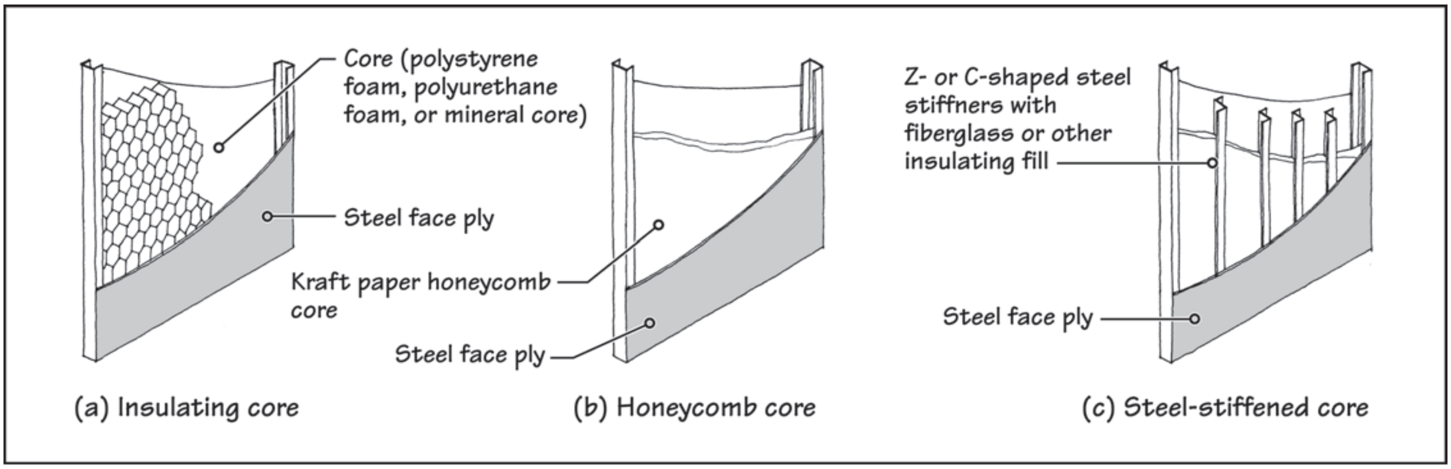
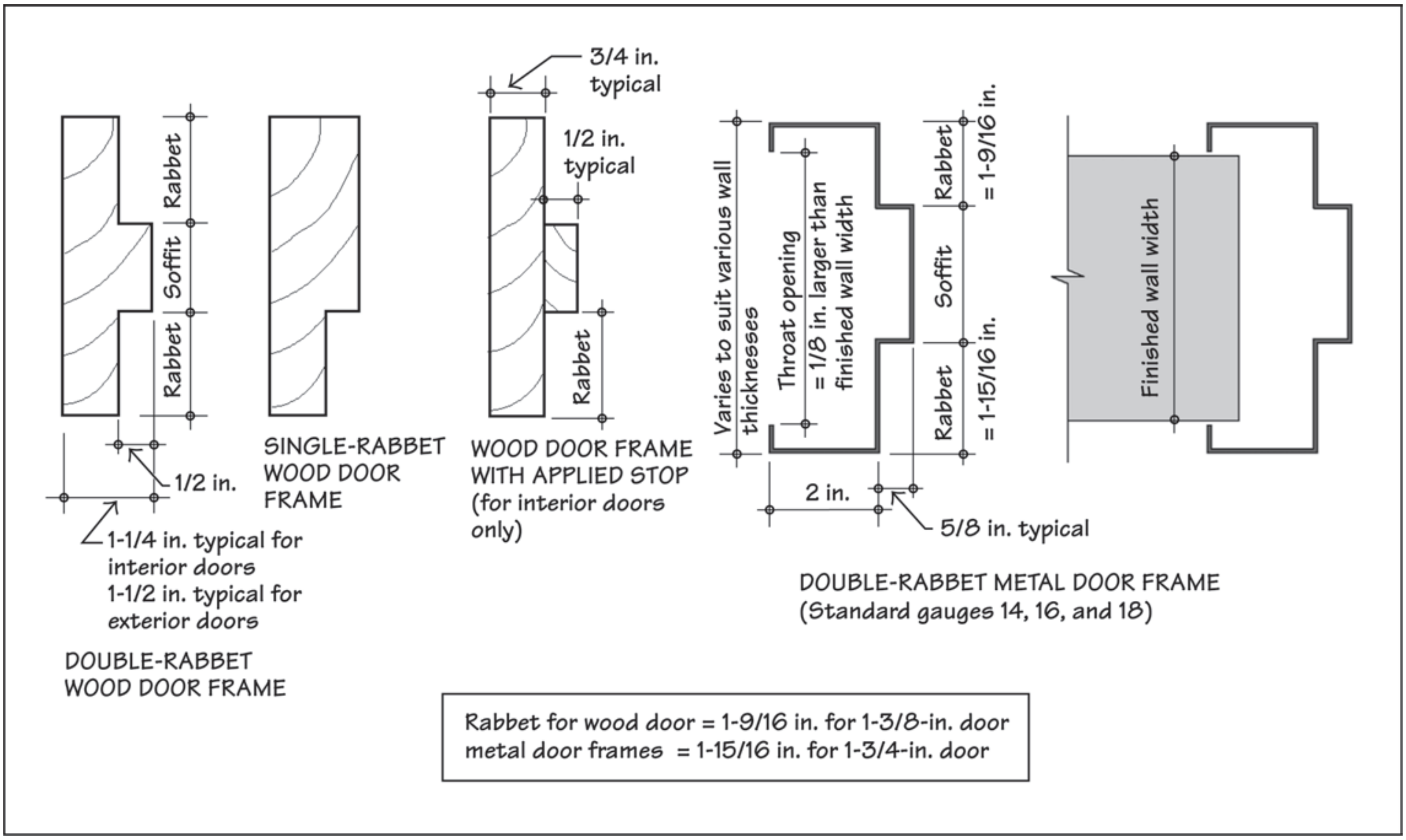

Core (polystyrene foam, polyurethane foam, or mineral core)
Steel face ply
Kraft paper honeycomb core
Steel face ply
Z- or C-shaped steel stiffners with fiberglass or other insulating fill
Steel face ply
(a) Insulating core
(b) Honeycomb core
(c) Steel-stiffened core

FIGURE 31.19 Anatomies of hollow metal flush doors.

31.6 DOOR FRAMES

Wood door frames are used with wood, fiberglass, and metal doors in non-fire-rated applications. Metal door frames, however, are used with metal doors or fire-rated wood doors. Figure 31.20 shows commonly used wood and metal door frame shapes, and Figures 31.21 and 31.22 show typical construction details of wood and metal door frames, respectively.


Rabbet
Soffit
Rabbet
1/2 in.
1-1/4 in. typical for interior doors
1-1/2 in. typical for exterior doors
DOUBLE-RABBET WOOD DOOR FRAME
SINGLE-RABBET WOOD DOOR FRAME
3/4 in. typical
1/2 in. typical
Rabbet
WOOD DOOR FRAME WITH APPLIED STOP (for interior doors only)
Varies to suit various wall thicknesses
Throat opening = 1/8 in. larger than finished wall width
Rabbet
Soffit
Rabbet
= 1-9/16 in.
= 1-15/16 in.
2 in.
5/8 in. typical
Finished wall width
DOUBLE-RABBET METAL DOOR FRAME (Standard gauges 14, 16, and 18)

Rabbet for wood door = 1-9/16 in. for 1-3/8-in. door
metal door frames = 1-15/16 in. for 1-3/4-in. door

FIGURE 31.20 Typical wood and metal door frame shapes.

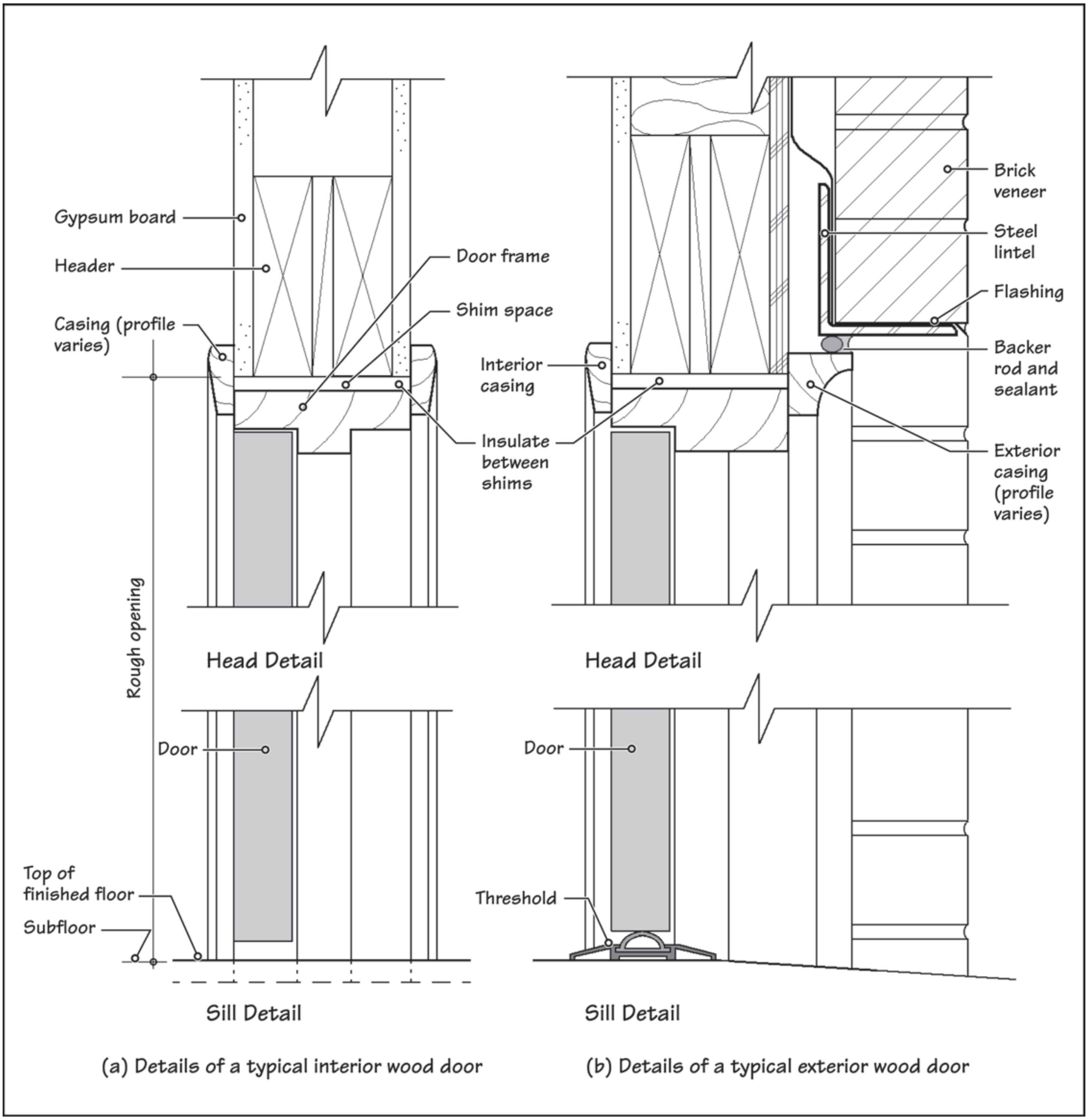
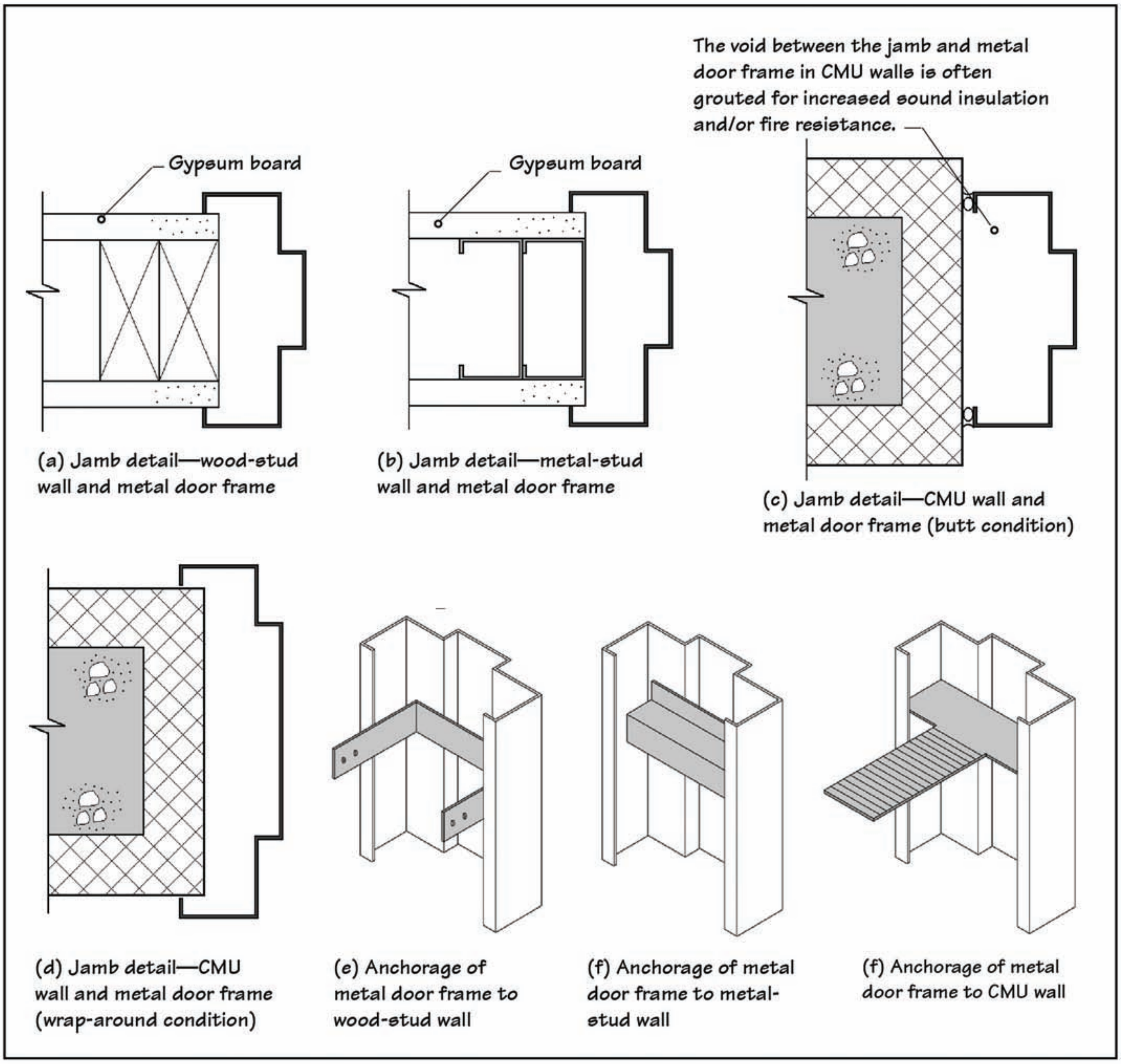

Gypsum board
Header
Casing (profile varies)
Door frame
Shim space
Insulate between shims
Rough opening
Head Detail
Door
Top of finished floor
Subfloor
Sill Detail
(a) Details of a typical interior wood door
Brick veneer
Steel lintel
Flashing
Backer rod and sealant
Interior casing
Exterior casing (profile varies)
Head Detail
Door
Threshold
Sill Detail
(b) Details of a typical exterior wood door

FIGURE 31.21 Head and sill details of typical interior and exterior wood doors.


Gypsum board
Gypsum board
The void between the jamb and metal door frame in CMU walls is often grouted for increased sound insulation and/or fire resistance.

(a) Jamb detail—wood-stud wall and metal door frame

(b) Jamb detail—metal-stud wall and metal door frame

(c) Jamb detail—CMU wall and metal door frame (butt condition)

(d) Jamb detail—CMU wall and metal door frame (wrap-around condition)

(e) Anchorage of metal door frame to wood-stud wall

(f) Anchorage of metal door frame to metal-stud wall

(f) Anchorage of metal door frame to CMU wall

FIGURE 31.22 Details of the anchorage of a metal door frame to various types of walls.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

9. The label on an NFRC-rated window must include the
- **a.** U-value and shading coefficient.
- **b.** U-value and air infiltration.
- **c.** U-value and solar heat gain coefficient.
- **d.** U-value and visible transmittance.
- **e.** Solar heat-gain coefficient and air infiltration.

10. In a window that carries the performance label "HS-C30 71 × 59", the number 30 indicates that the window
- **a.** will leak a maximum of 30% of the room's air per hour.
- **b.** conforms to the applicable standard up to a size of 30 in. × 30 in.
- **c.** should not be subjected to a maximum wind load of 30 psf.
- **d.** should not be subjected to a maximum combined wind load and vapor pressure of 30 psf.
- **e.** none of the above.

11. In a window that carries the performance label "HS-C30 71 × 59", the letter C indicates that the window
- **a.** belongs to a performance class called commercial.
- **b.** is a casement window.
- **c.** is a C-grade window.
- **d.** none of the above.

12. Nailing flanges are only provided in steel windows.
- **a.** True
- **b.** False

13. The use of nailing flanges in windows also requires the use of
- **a.** retainer clips.
- **b.** two L-shaped trims.
- **c.** none of the above.
- **d.** both (a) and (b).
- **e.** either (a) or (b).

14. Most windows are shop-glazed so that they arrive at the construction site in a fully assembled condition.
- **a.** True
- **b.** False

15. A hollow metal door frame is obtained from
- **a.** tubular steel.
- **b.** sheet steel that is pressed into shape.
- **c.** tubular steel and sheet steel welded together.
- **d.** none of the above.

16. A hollow metal door frame is installed so that it
- **a.** butts against the jambs of a CMU wall.
- **b.** wraps around the jambs of a CMU wall.
- **c.** (a) or (b).
- **d.** (a) and (b).

31.7 FIRE-RATED DOORS AND WINDOWS

A fire-rated wall can serve as a barrier to the spread of fire only if the openings (doors, shutters, and windows) installed in them also provide the same (or nearly the same) degree of fire protection. Building codes require a certain minimum level of fire protection of openings provided in fire-rated walls.

The *fire-protection ratings* of openings are usually allowed to be lower than the fire-resistance ratings of the walls in which they are installed. For example, the fire rating of a door in a wall is 75% of the fire rating of the wall. Thus, in a 2-h-rated wall, a $1\frac{1}{2}$-h-rated door is considered adequate. An opening with a lower fire-protection rating than the wall in which it is installed does not greatly compromise the overall integrity of the wall. This is true because, under normal conditions of use, there is usually a lower fire hazard in the vicinity of an opening compared with the rest of the wall.

For example, in the case of a door, there is a clear space on both sides of the door to provide for unobstructed traffic. Hence, there is less fuel available in close proximity to the door, and the resulting fire hazard is less than that in the rest of the wall. Another reason is that the total opening area in fire-rated walls is usually so limited by building codes that a lower protection of openings does not greatly reduce the overall effectiveness of the wall.

Reference to a *rated opening* implies that the entire assembly is rated. The assembly consists of the door (or window), door frame (or window frame), anchorages, sill, handles, latches, hinges, and so on. Building codes require that a fire-rated door or window and its frame bear a label indicating that the assembly has been tested by an approved, independent testing laboratory.

Note that in referring to the fire rating of openings, the term *fire-protection rating*, not fire-resistance rating, has been used. This is because the fire rating of openings is not determined by the same test used for the fire rating of walls (the ASTM E 119 test).

FIRE DOORS

A fire door may be a 3-h-, 90-min-, 60-min-, 45-min-, or 20-min-rated door. A 20-min-rated door assembly is, in fact, a smoke-and-draft-control assembly. Its main purpose is to minimize the transmission of smoke from one side of the door to the other. A 20-min door is usually required in a 1-h-rated corridor wall. A $1\frac{3}{4}$-in.-thick solid-bonded wood-core door usually provides 20-min protection. However, to be accepted as a 20-min door, it must pass the required test to substantiate performance.

FIRE WINDOWS

Where the walls (interior or exterior) are required to be fire rated, a glazed window placed in such walls must provide at least 45-min protection. A glazed window with 45-min protection is referred to as a *fire window*. Because 45-min protection is relatively low for a protected opening, building codes place restrictions on the allowable areas of fire windows.

EXPAND YOUR KNOWLEDGE

Window Terminology

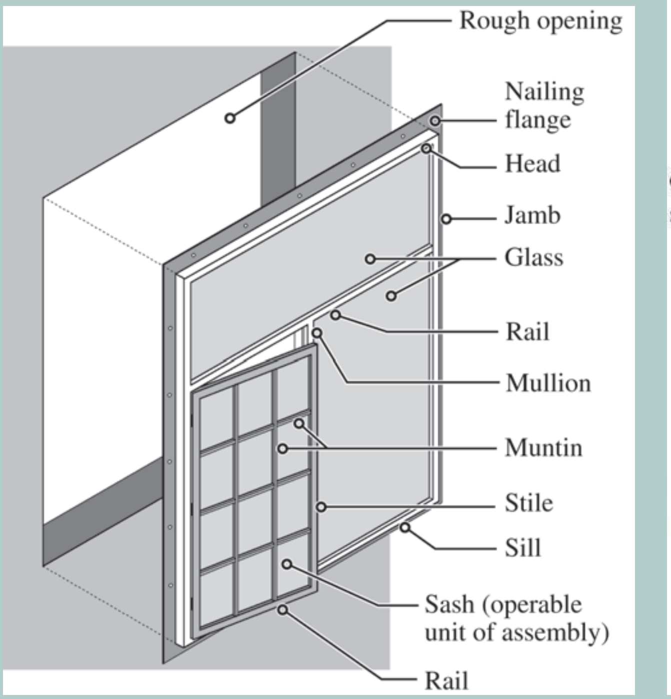
Two important components of a window are (a) window frame and (b) window sash. The terminology related to these and other components of a window is given next.

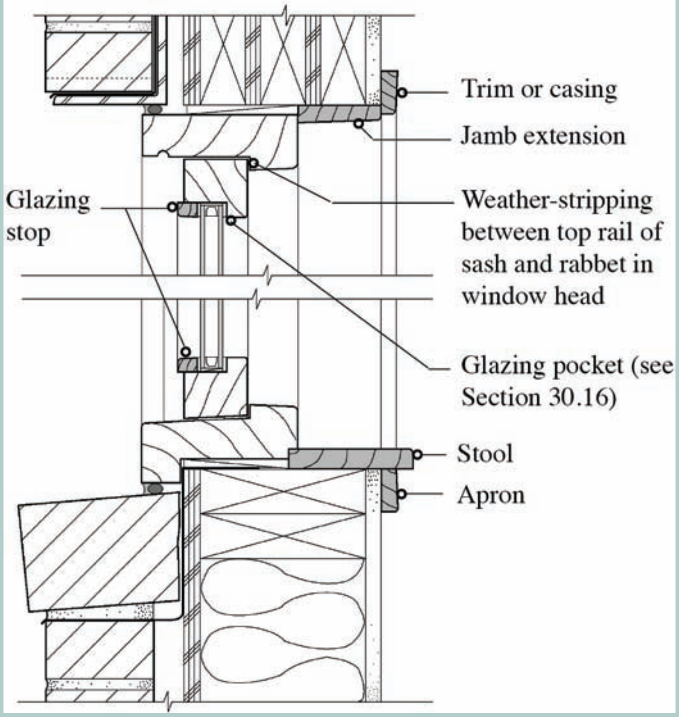
Frame (the Fixed Part of the Window Assembly)

- *Head*—the top horizontal member of the frame
- *Jamb*—a side vertical member of the frame
- *Sill*—the bottom horizontal member of the frame
- *Mullion*—an intermediate vertical member of the frame
- *Rail*—an intermediate horizontal member of the frame
- *Nailing flange*—Some manufacturers provide windows with a nailing flange. A nailing flange runs continuously around the outside of a window frame and functions as a flashing. It also provides a means of anchoring the window to the wall opening.

Sash (the Operable Part of the Window Assembly)

- *Stile*—a vertical sash member
- *Rail*—a horizontal sash member
- *Muntins*—thin horizontal and vertical dividers, commonly used in early windows when large sheets of good-quality glass were not available. (In some contemporary windows, large sheets of glass are used, but to simulate a divided window, grilles are used within the cavity of an insulating glass unit. Alternatively, a grill may be placed over the glass pane, either on the inside face, the outside face, or both faces. The grilles are removable for easy cleaning of glass. A window with imitation muntins is referred to as comprising *simulated divided lites*. A window with true dividers is referred to as a window with *authentic*, or *true*, *divided lites*.)
- *Weatherstripping*—a strip of resilient material that provides a seal between the sash and the frame to reduce air and water leakage
- *Glazing stop*—a feature that holds the glass against the rabbet in the sash or frame
- *Rabbet*—a step in a sash or frame cross section against which the glass is held
- *Gasket*—a strip of resilient material between the glass and the glazing pocket. (Double-sided tape is used


Rough opening
Nailing flange
Head
Jamb
Glass
Rail
Mullion
Muntin
Stile
Sill
Sash (operable unit of assembly)
Rail


Trim or casing
Jamb extension
Glazing stop
Weather-stripping between top rail of sash and rabbet in window head
Glazing pocket (see Section 30.16)
Stool
Apron

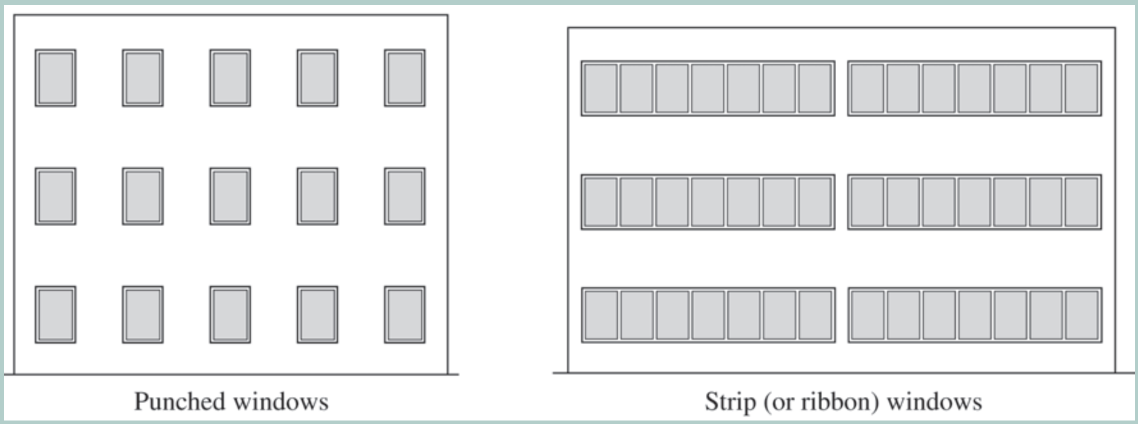
by some window manufacturers instead of a gasket.)
- *Daylight opening (DLO)*—visible glass area in a window. (It is the total area of glass minus the invisible area, i.e., the area of glass that is buried within glazing pockets.)
- *Hardware*—hinges, latches, locks, levers, and so on

Window Surrounds (Interior)

- *Stool*—a horizontal trim member that abuts against the window sill and covers the rough sill
- *Jamb extension*—a horizontal or vertical trim that covers the rough head and jamb and extends the depth of the window frame. (Note that the term *jamb extension* also refers to the extension of the head because the head is sometimes referred to as the *head jamb*.)
- *Apron*—the trim installed on the wall under the stool
- *Casing* (or trim)—decorative members that cover the joints between adjacent materials

Window-Opening Configurations

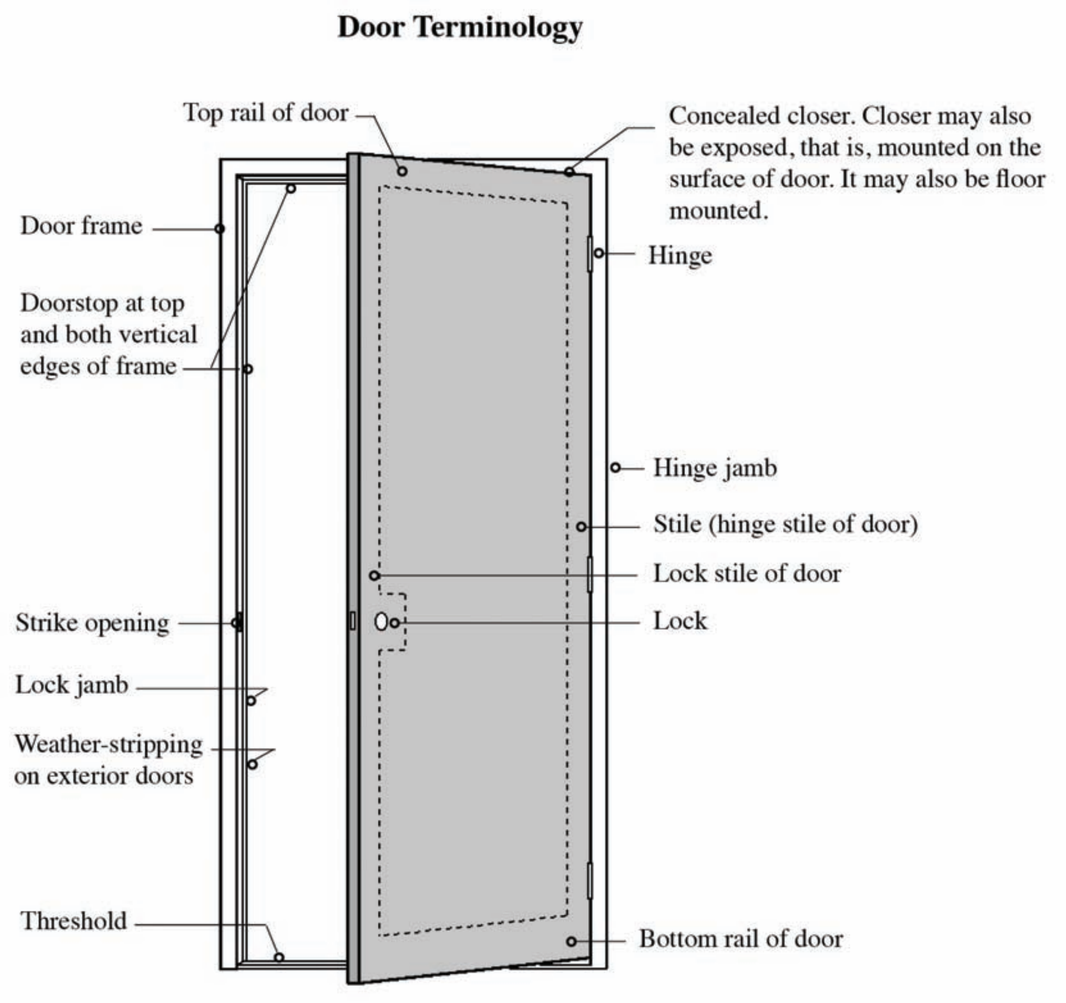
- *Rough opening*—the opening within which the window is placed. (Rough opening dimensions are at least $\frac{1}{2}$ in. greater than the actual window unit dimensions to allow an easy fit and alignment of the window in the opening. The terms *rough sill, rough head,* and *rough jamb* refer to the respective areas of a rough opening.)
- *Punched window and punched glazing*—a window with an opaque wall around it. (The term *punched glazing* is generally used for large, fixed glazing in which the glass is site installed. In terms of appearance, both punched windows and punched glazing are the same.)
- *Strip windows and glazing*—an array of windows placed side by side to form a horizontal strip (or ribbon) window system. (The term *strip glazing* is used with large, fixed glazing units in which the glass is site installed.)
- *Window wall and glass curtain wall*—a wall in which the windows extend from floor to roof, or from floor to floor, called a *window wall*. (A window wall must be distinguished from a glass curtain wall, which hangs as a curtain from the building's structure and bypasses the intermediate floors or roof; see Chapters 27 and 32)
- *Projected window*—includes windows whose sashes project out of the window plane when open, such as casement, awning, hopper, and pivoted windows. (Projected windows are generally more airtight in the closed position than hung or sliding windows because of the pressure seal between the frame and the sash.)


Punched windows

Strip (or ribbon) windows

(*Continued*)

EXPAND YOUR KNOWLEDGE (*Continued*)


Door Terminology
Top rail of door
Concealed closer. Closer may also be exposed, that is, mounted on the surface of door. It may also be floor mounted.
Door frame
Hinge
Doorstop at top and both vertical edges of frame
Hinge jamb
Stile (hinge stile of door)
Lock stile of door
Strike opening
Lock
Lock jamb
Weather-stripping on exterior doors
Threshold
Bottom rail of door

PRINCIPLES IN PRACTICE

A Note on Aluminum

Aluminum is a metal whose appearance resembles and whose corrosion resistance matches that of stainless steel. It is, however, much lighter, softer, and more flexible than steel or stainless steel. Its softness allows it to be easily extruded into complex cross-sectional profiles. Its flexibility allows aluminum components to be joined together by the snap-on technique, requiring no fasteners. Its corrosion resistance implies that it can be left exposed to the atmosphere without any protective coating.

Corrosion resistance, flexibility, and softness are the reasons aluminum is the preferred metal for glass curtain walls, storefronts, and windows. Nearly one-third of the entire production of aluminum is used in these components [Ref. 31.1] provided. Aircrafts and automobiles also consume a large portion of the aluminum produced.

Aluminum, in the form of aluminum oxide, is far more abundant on the Earth's crust than any other metal oxide, and most rocks and soils contain some aluminum oxide. However, the energy required to extract aluminum from common rocks and soils is very high. The only economical method of producing aluminum is from the ore called *bauxite*, named after Baux, a town in southern France. Bauxite ore contains nearly 60% aluminum oxide and 40% of other compounds, such as iron oxide and silicon oxide. Producing aluminum, even from bauxite ore, is an energy-intensive process. This explains why, weight for weight, aluminum is more expensive than steel, despite aluminum's relative abundance on the Earth. It also explains why the aluminum-manufacturing industry resorted to recycling of cans and other scrap well before other industries contemplated sustainable manufacturing.

Like other pure metals, pure aluminum is too weak and soft to be used as a building material. Small amounts (altogether up to 5%) of other elements, such as copper, zinc, silicon, iron, magnesium, and manganese, alloyed with aluminum make it a more practical metal. Numerous aluminum alloys are available to suit different applications. However, pure aluminum is more corrosion resistant than its alloys. Therefore, where corrosion resistance is critical, anodized or painted aluminum is used.

The higher corrosion resistance of pure aluminum is exploited in the metal called *alclad*. Alclad contains an aluminum alloy core that is metallurgically bonded to pure aluminum on the surface. It is a more expensive process than anodizing and is commonly used in aircraft.

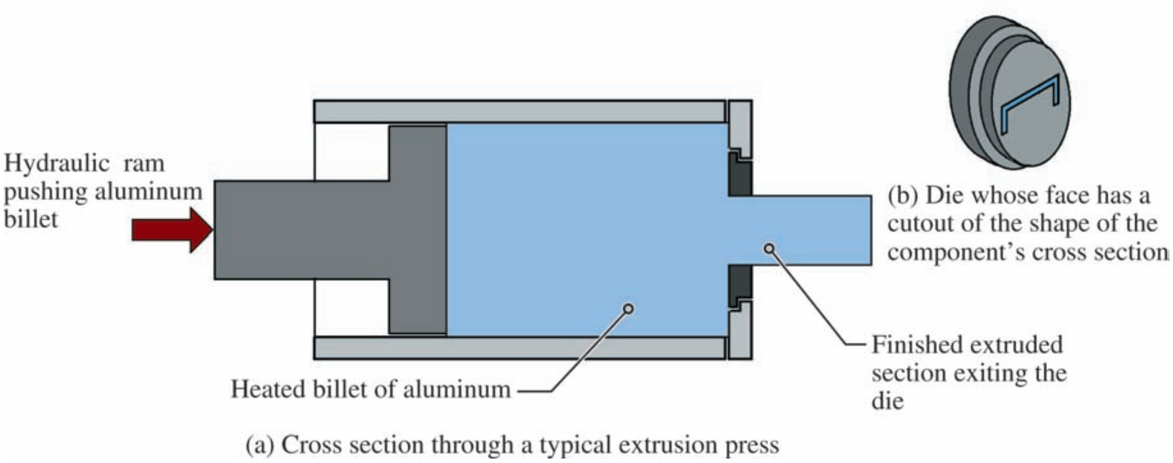

Hydraulic ram pushing aluminum billet
(b) Die whose face has a cutout of the shape of the component's cross section
Finished extruded section exiting the die
Heated billet of aluminum
(a) Cross section through a typical extrusion press

FIGURE 31.23 Aluminum window and curtain wall sections are made by pushing a heated aluminum billet through a die, a process called extrusion. Extrusion is similar to pushing toothpaste through the opening of a toothpaste tube.

ALUMINUM EXTRUSIONS

Manufacturing aluminum from bauxite ore has several similarities to manufacturing iron from its ore. The end product is cast pig aluminum, which is converted to aluminum billets, bloom, or slabs. Aluminum sections can be made by hot rolling billets in the same way as steel sections.

Sheets obtained from aluminum slabs can be cold-formed into simpler profiles, similar to light-gauge steel members. However, extrusion is a cheaper and more versatile process for aluminum than hot rolling or cold forming. Additionally, fairly complex cross-sectional shapes that cannot be obtained from hot rolling can be produced by extruding. Therefore, except for sheets, most architectural aluminum components are produced from the extrusion process, Figure 31.23.

The melting point of most aluminum alloys is nearly 1,100°F (600°C). Therefore, extrusion requires aluminum billets to be heated to a fairly low temperature—nearly 800°F (450°C). In this process, a billet of heated aluminum is pressed through a die, whose face has a cutout that matches the cross-sectional profile of the desired component. A different cross-sectional profile needs only a different die, which is not too expensive to fabricate.

ANODIZED ALUMINUM

Aluminum obtains its corrosion resistance because of the aluminum oxide film it develops on its surface on exposure to the atmosphere. This occurs fairly quickly. In fact, the extrusion emerging out of the die mouth is already covered with an oxide film. Like the chromium oxide film on stainless steel, aluminum oxide film is also self-repairing.

The aluminum surface obtained from the die is referred to as *mill finish*. Mill-finished aluminum has a bright, silvery (the familiar aluminum foil) finish, which turns dull gray after a few years. The number of years depends on the amount of pollution and the amount of rainfall. If water from rain or condensation is allowed to lodge on the surface, black streaks may develop there.

Most architectural aluminum is, therefore, either anodized or painted. Anodization essentially preoxidizes the aluminum. The only difference between natural mill-finished aluminum and anodized aluminum is in the thickness of the oxide film. The natural oxide film is nearly one-millionth of an inch (0.001 mil) thick. The anodic coating is several thousand times thicker—nearly 0.2 to 0.7 mil thick. A thicker coating is selected for exterior exposures. Coatings greater than 3 mil fracture and chip easily.

The anodic coating may either be clear or colored. A clear coating leaves aluminum looking its natural silvery color. It is also the more common and economical finish and has been used in several outstanding building facades.

The colors available in anodized aluminum are fairly limited. Generally, they are restricted to black, dark bronze, medium bronze, light bronze, and white, and there can be slight variations between pieces.

PAINTED ALUMINUM

Two types of paint finishes are commonly used on aluminum:

- Baked-enamel coating
- Fluoropolymer coating

(Continued)

PRINCIPLES IN PRACTICE

A Note on Aluminum (*Continued*)

A baked-enamel coating requires pretreatment of mill-finished aluminum with required chemical(s), followed by spray application of a thermosetting, modified acrylic enamel coating, followed by oven baking. A baked-enamel finish is generally recommended for interior applications. The colors obtained are uniform and opaque.

A fluoropolymer coating involves pretreatment of mill-finished aluminum with pretreatment chemicals, followed by one to four coats of a thermocured product system containing not less than 70% polyvinylidene fluoride (PVDF) resin, known in the industry as KYNAR 500® and HYLAR 5000.

A PVDF finish is strong and durable and is primarily suited for exterior applications. A wide range of colors, including exotic colors, is available. Two types of durability ratings with respect to PVDF finish are available; one gives five years of performance at the test requirements and another gives 10 years.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

17. Which of the following terms is used with fire-rated windows or doors?
- **a.** *Fire-resistance rating*
- **b.** *Fire-protection rating*

18. Fire-rated doors are rated as
- **a.** 3 h, 90 min, 60 min, 45 min, or 20 min.
- **b.** 3 h, 120 min, 60 min, or 30 min.
- **c.** 4 h, 3 h, 2 h, 1 h, or 30 min.
- **d.** 4 h, 3 h, 2 h, or 1 h.
- **e.** none of the above.

19. Which of the following terms describes an intermediate vertical member of a window frame?
- **a.** *Mullion*
- **b.** *Stile*
- **c.** *Rail*
- **d.** *Jamb*
- **e.** *Muntin*

20. Which of the following terms describes an intermediate horizontal member of a window frame?
- **a.** *Mullion*
- **b.** *Stile*
- **c.** *Rail*
- **d.** *Jamb*
- **e.** *Muntin*

21. Which of the following terms refers to thin and narrow horizontal and vertical members of a window sash?
- **a.** *Mullion*
- **b.** *Stile*
- **c.** *Rail*
- **d.** *Jamb*
- **e.** *Muntin*

22. A stool is used in a window in the building's interior.
- **a.** True
- **b.** False

REVIEW QUESTIONS

1. Sketch the following window styles: (a) casement window, (b) double-hung window, (c) single-hung window, (d) awning window, and (e) hopper window.
2. A window has been rated as HS-C35 71 × 59. Explain each term of the rating.
3. Which materials are commonly used for cladding wood windows? What is the purpose of cladding, and which parts of a window are clad? Explain how the cladding helps to secure a window to the opening.
4. What does the acronym *NFRC* stand for? List the information provided in an NFRC label.
5. Explain the purpose and anatomy of a nailing flange. Which types of windows are typically provided with nailing flanges?
6. Sketch in plan various types of wood door frames, and give the terminology used to describe various parts of a door frame.
7. Sketch in plan a hollow metal door frame and its junction with (a) a metal-stud wall and (b) a CMU wall.
8. Using sketches, explain the following terms: (a) *punched windows,* (b) *strip windows,* (c) *window wall,* and (d) *curtain wall*.

CHAPTER 32

Exterior Wall Cladding–IV (Wall Systems in Glass)

CHAPTER OUTLINE

32.1 GLASS-ALUMINUM CURTAIN WALLS

32.2 ANCHORAGE OF A STICK-BUILT GLASS CURTAIN WALL TO A STRUCTURE

32.3 STICK-BUILT GLASS CURTAIN WALL DETAILS

32.4 UNITIZED GLASS CURTAIN WALL

32.5 STRUCTURAL PERFORMANCE OF A GLASS-ALUMINUM WALL

32.6 ENVIRONMENTAL PERFORMANCE CRITERIA FOR A GLASS CURTAIN WALL

32.7 OTHER GLASS-ALUMINUM WALL SYSTEMS

32.8 NONTRADITIONAL GLASS WALLS

Transparency, luminosity, and elegance are the reasons for the popularity of glass walls in modern architecture. Most glass walls are constructed with aluminum sections to support the glass. In other words, the glass panes (also called *lites*) are held within vertical and horizontal aluminum framing members. Therefore, they share some of the characteristics of their smaller counterparts—the aluminum windows, discussed in Chapter 31. However, there are many differences between the two: scale, aesthetic character, performance properties, design, detailing, and installation.

Three commonly used glass-aluminum wall system systems are:

- Glass-aluminum curtain walls
- Punched and strip glazing systems
- Storefront systems

The vast majority of contemporary buildings include one or more of these systems in the same building. The reasons include the unparalleled opportunity provided by them to obtain the maximum amount of daylight and view, the cost savings compared with other exterior wall cladding systems, and the recent technological advances in the thermal and structural performance of glass wall systems.

Of the three systems listed above, the most frequently used and the most complex is the glass-aluminum curtain wall system, which is presented here in detail. The other two systems (strip system and storefront system) are discussed to the extent that they differ from the curtain wall system. Finally, the chapter deals with nontraditional glass wall systems—systems that do not include aluminum sections to support the glass.

32.1 GLASS-ALUMINUM CURTAIN WALLS

Because of their common use, glass-aluminum curtain walls (or simply *glass curtain walls*) are constantly evolving in their design and performance. Therefore, a succinct classification that includes all contemporary glass curtain walls is impossible. The American Architectural Manufacturers Association (AAMA), an association of the manufacturers of windows and curtain walls, however, classifies glass curtain wall systems into five types based on their anatomy:

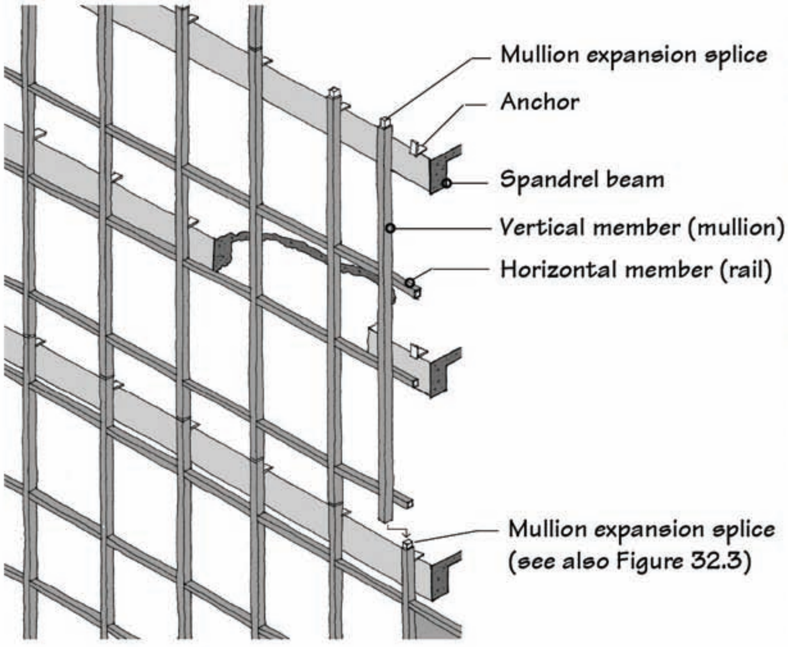
- Stick-built (or, simply, stick) systems
- Unitized systems
- Unit and mullion systems
- Panel systems
- Column cover and spandrel systems

These systems are illustrated in Figure 32.1. The stick system is the oldest and the most widely used system. The remaining four systems are different from the stick system because they consist of prefabricated wall units similar to the (opaque) curtain wall panels.

STANDARD AND CUSTOM CURTAIN WALL SYSTEMS

Most major glass curtain wall manufacturers have their own facility for extruding the aluminum sections. Walls constructed from a manufacturer's commonly used and pretested aluminum sections are referred to as *standard walls*.

Custom curtain walls utilize cross-sectional shapes extruded specifically for a project in response to an architect's design. Because the cost of dies and other equipment required to extrude custom cross sections can be recovered from just one fair-size project, custom curtain walls are fairly common. Custom walls should, however, be tested for performance before they are used in a project. Performance data for standard walls are available from the manufacturers.



(a) STICK SYSTEM

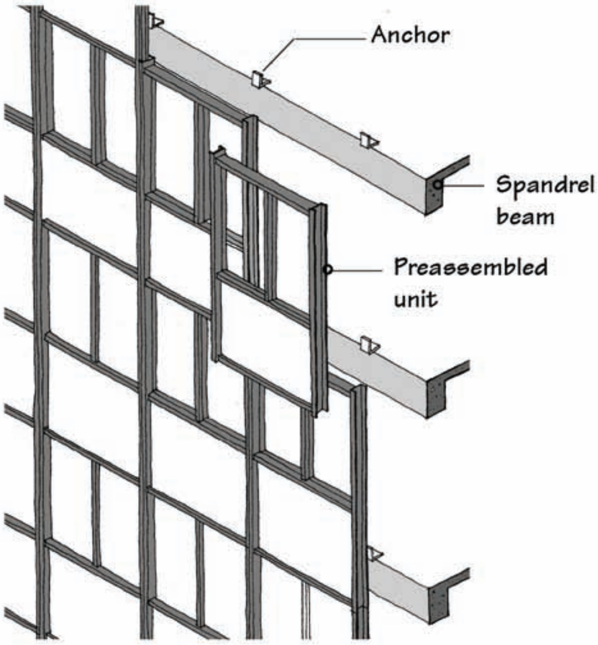
In the stick system, the curtain wall is installed piece by piece at the site. Generally, the mulions are installed first, followed by the rails. Subsequently, the glass panes are installed within the mullion-rail framework.

The anchorage of the wall to the structural frame is through the mullions. The mullions may span from floor to floor or over two floors. Thermal expansion and contraction of mullions is accomodated through expansion joints in mullions.

The system components are shop-fabricated and shipped to the construction site in knocked-down (KD) version. Therefore, it has relatively low shipping costs and also permits a greater degree of on-site adjustment, as compared to the other systems.

Its disdavantage include longer on-site assembly time and more on-site labor than the other systems.

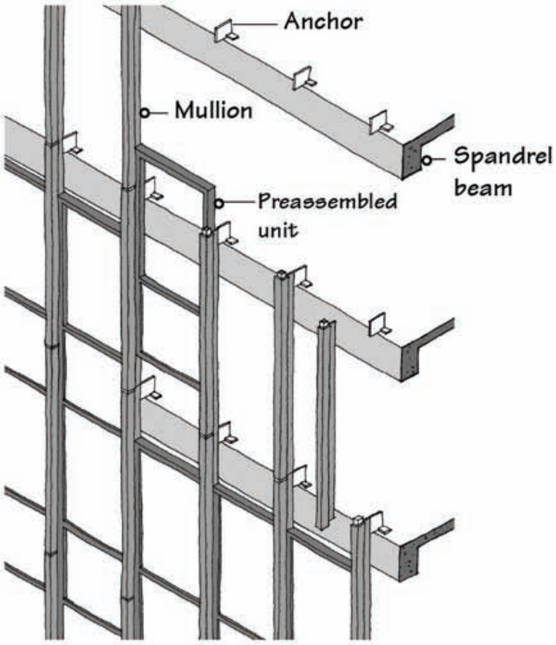
FIGURE 32.1 Types of glass curtain walls—the stick system. (Illustration adapted from AAMA, Curtain Wall Design Guide, 1996.)



(b) UNITIZED SYSTEM

A unitized system consists of framed wall units that are shop-fabricated, preassembled, and generally preglazed. The units are designed so that the vertical and horizontal members in adjacent units interlock to form common mullions and rails. The units may be one or two stories high. They are anchored to the building's structural frame in essentially the same way as the mullions in the stick system.

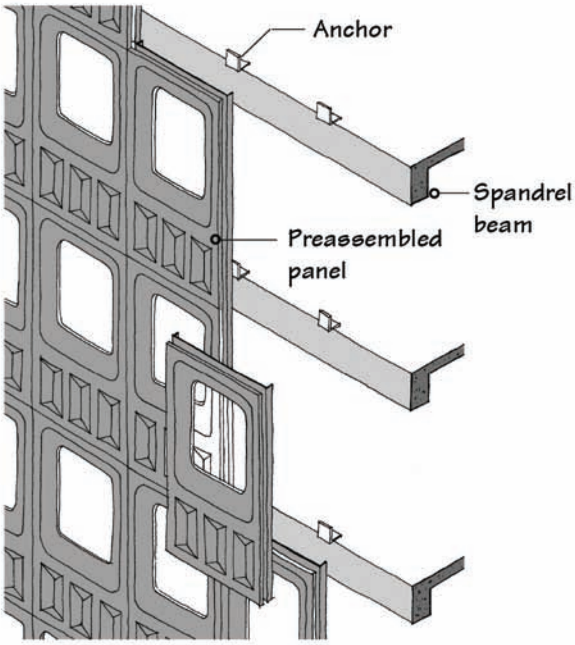
The advantage of this system is its greater degree of quality control resulting from shop fabrication. Its disadvantage is the greater shipping cost because of the added bulk from assembled units, the need for a greater degree of protection of units during transportation and a lower degree of field adjustment.



(c) UNIT AND MULLION SYSTEM

The unit and mullion system combines the advantages of both the stick system and the unitized system. It is constructed by first installing the mullions and subsequently factory assembled units are placed between the mullions.

Because the system is a compromise between the stick and the unitized system, it has the advantages and disadvantages of both, that is, its transportation cost is lower than that of the unitized system but greater than that of the stick system. A greater degree of site adjustability is available in unit and mullion system but it is less than that of the stick system.



(d) PANEL SYSTEM

The panel system consists of preassembled (and sometimes preglazed) homogeneous sheet metal panels with glass infills that generally span floor to floor. The curtain wall's appearance is more integrated and comprehensive rather than a grid pattern of horizontal and vertical elements.

The panels can be formed by stamping or casting. The casting system is economical only where a large number of identical panels are needed.

FIGURE 32.1 (*Continued*) Types of glass curtain walls—unitized system, unit and mullion system, and panel system. (Illustrations adapted from AAMA, Curtain Wall Design Guide, 1996.)

Walls made from standard components are obviously more economical. However, this does not imply that the standard components yield only one type of wall design. In fact, the components are generally quite adaptable, and manufacturers can provide a few custom components for a standard system, so that the facade expressions obtained from the use of standard components can be numerous. If the number of custom components in a wall becomes excessive, the cost of a standard wall may approach that of a custom wall.

(e) COLUMN COVER AND SPANDREL SYSTEM
This system, though not a true glass curtain wall system, consists of separate column covers connected to spandrel covers that generally span from column to column. Infill glazing units may either be preassembled or assembled at the site like those of a stick-built system.

The system provides an independent expression of the structural system rather than concealing it behind a (more homogeneous) wall.

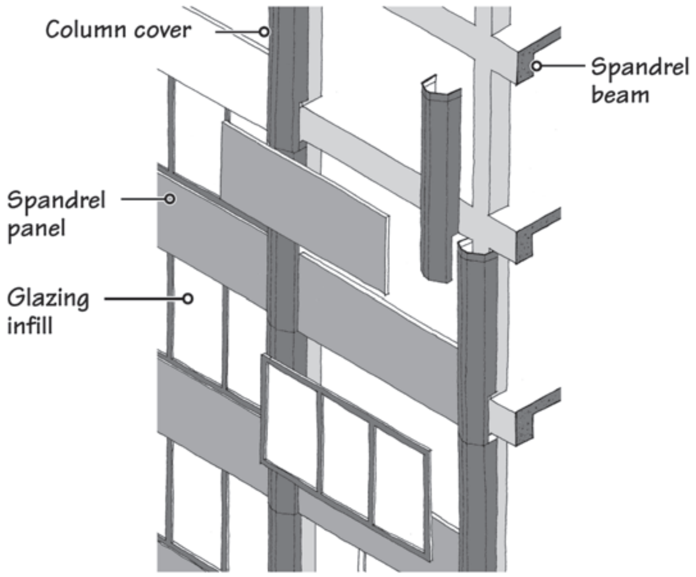


FIGURE 32.1 (*Continued*) Types of glass curtain walls—column cover and spandrel system. (Illustration adapted from AAMA, Curtain Wall Design Guide, 1996.)

32.2 ANCHORAGE OF A STICK-BUILT GLASS CURTAIN WALL TO A STRUCTURE

Like other curtain walls, a glass curtain wall must be spaced away from the building's structural frame to account for the small dimensional variations (within the allowed tolerances) in the structural frame. A 2-in. space is generally the minimum requirement. A wider space may be required for tall buildings.

DEAD-LOAD ANCHORS AND EXPANSION ANCHORS

As shown in Figure 32.1(a), a stick-built glass curtain wall consists of vertical members (*mullions*) and horizontal members (*rails*). The profiles of both mullions and rails are almost identical and are tubular in cross section.

The wall is anchored to the building's structural frame through the mullions. All mullions in a wall are installed first; then the rails are inserted between them. Three rails are commonly used per floor to create two separate areas of glass at each floor—vision glass and spandrel glass.

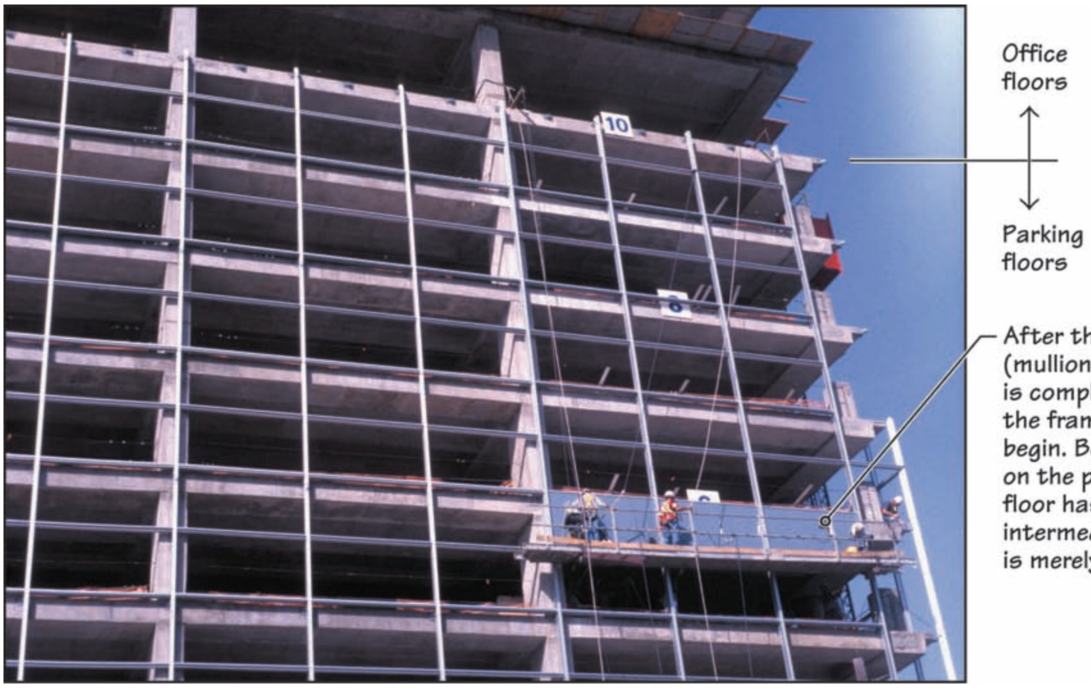
In a building (or part of a building) where there is no vision glass, such as in a multistory parking garage, intermediate rails are needed only to reduce the size of glass panes. Two rails per floor are commonly used in that situation, Figure 32.2. The center-to-center spacing between mullions is generally 4 ft to 6 ft, depending on the lateral load intensity and the desired appearance of the facade.

To allow for the expansion and contraction of mullions caused by temperature changes, each mullion must be provided with expansion joints. Thus, the mullions consist of short lengths (one or two floors tall) that terminate in expansion joints at both ends, Figure 32.3.

An expansion joint also absorbs the creep in concrete columns and the live-load deflection of the spandrel beam to which the mullions are anchored. Therefore, the expansion joint width must be determined on a project-by-project basis. Note that an expansion joint allows movement in the vertical direction only.

Because all loads on a wall are transferred to the structural frame through the mullions, each mullion is provided with a dead-load support anchor (or, simply, a *DL anchor*) designed to carry the weight of the respective portion of the curtain wall.

A DL anchor fully restrains the movement of a mullion; that is, the mullion is immobile in all three principal directions at a dead-load support. Therefore, a DL anchor transfers both the dead loads and the lateral loads on a mullion to the building's structural frame.



After the framing of the curtain wall (mullions and rails) for the parking floors is complete, its glazing has started, while the framing for the office floors is yet to begin. Because there are no vision areas on the parking floors, the glazing on each floor has been divided into two parts by one intermediate rail. The purpose of the rail is merely to reduce the size of the glass.

FIGURE 32.2(a) The progress in the installation of a stick-built glass curtain wall on an office building in which the lower floors are parking floors and the upper floors are office floors. See also Figure 32.2(b).

In this photograph, the glazing of the curtain wall on the parking floors of the building shown in Figure 32.2(a) is almost complete. Now the framing for the curtain wall on the office floors has begun. As shown here, the mullions are installed first, followed by the rails.

This (part of the) photograph shows the progress in the installation of rails on the office floors. Because an office floor has separate spandrel and vision glass areas, there will be three rails per floor.

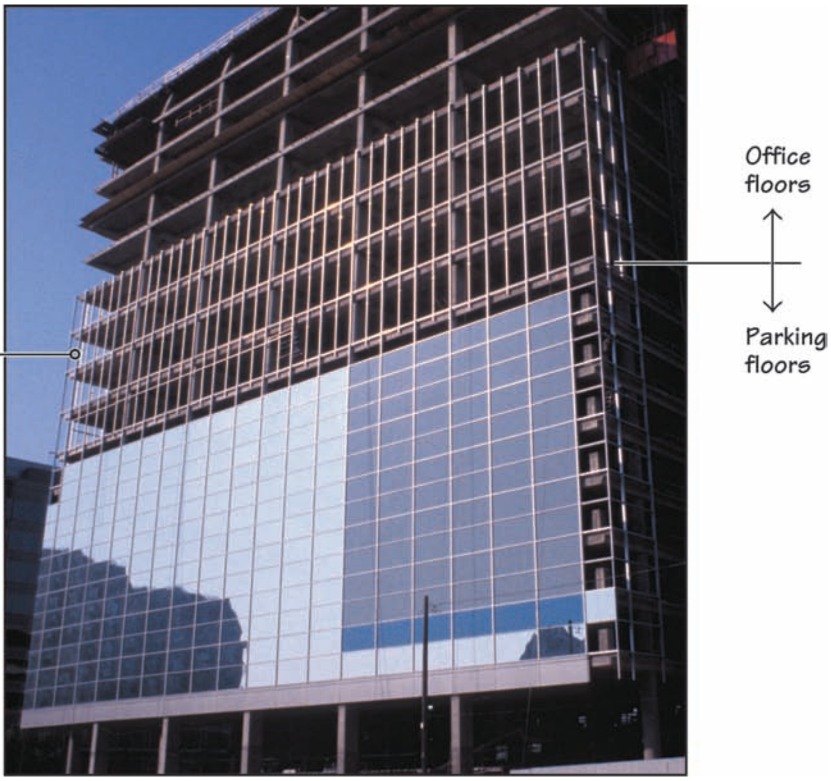


FIGURE 32.2(b) The progress in the installation of a stick-built glass curtain wall on an office building in which the lower floors are parking floors and the upper floors are office floors; see also Figure 32.2(a).

Two types of mullion spans are generally used in a stick-built glass curtain wall, Figure 32.4:

- Single-span mullion systems
- Twin-span mullion systems

In a single-span mullion system, each mullion extends only over one floor. DL anchors are, therefore, required at every floor, except at the ground floor, where the building's foundation provides dead-load support to the first mullion length, Figure 32.4(a).

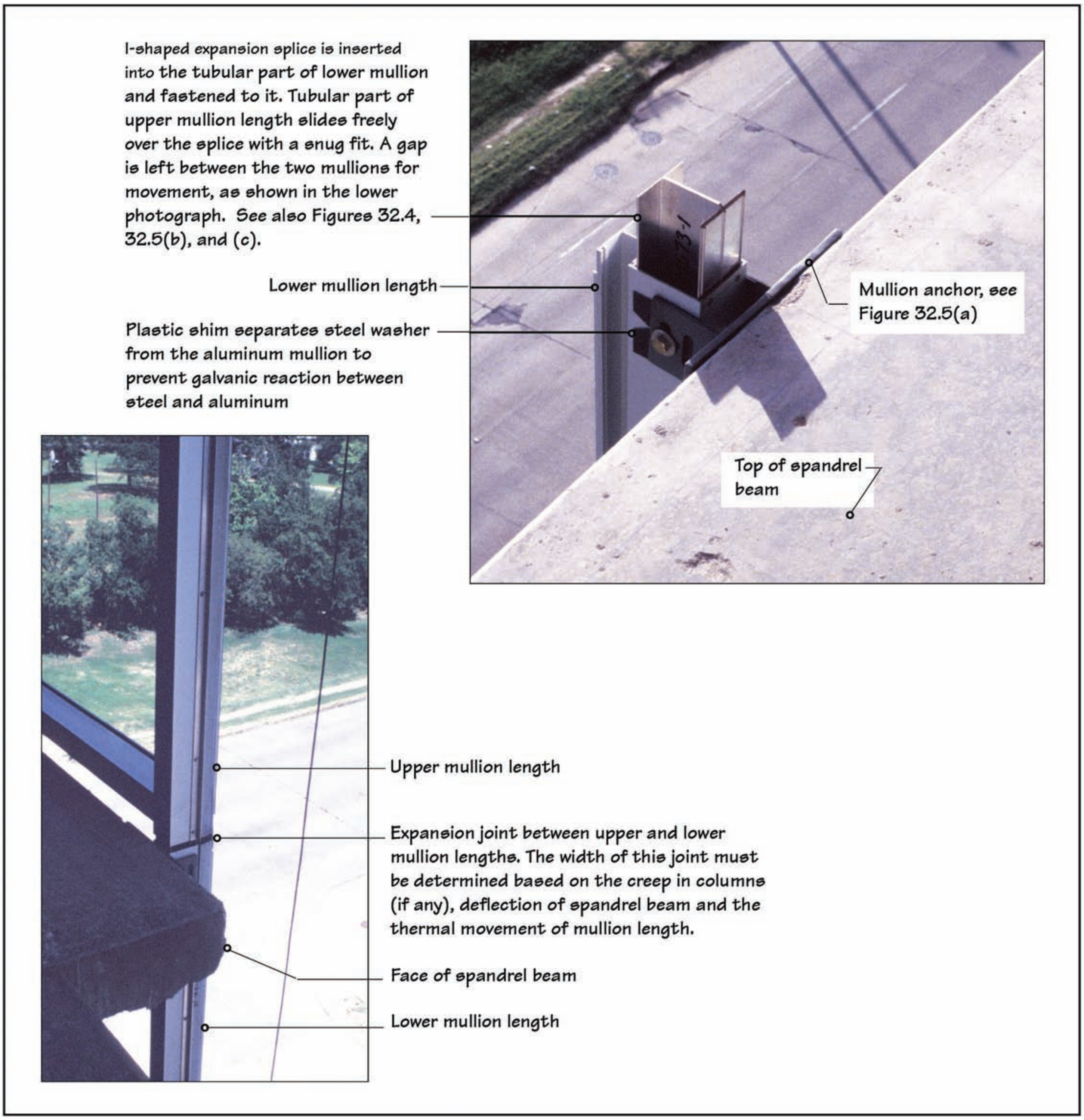
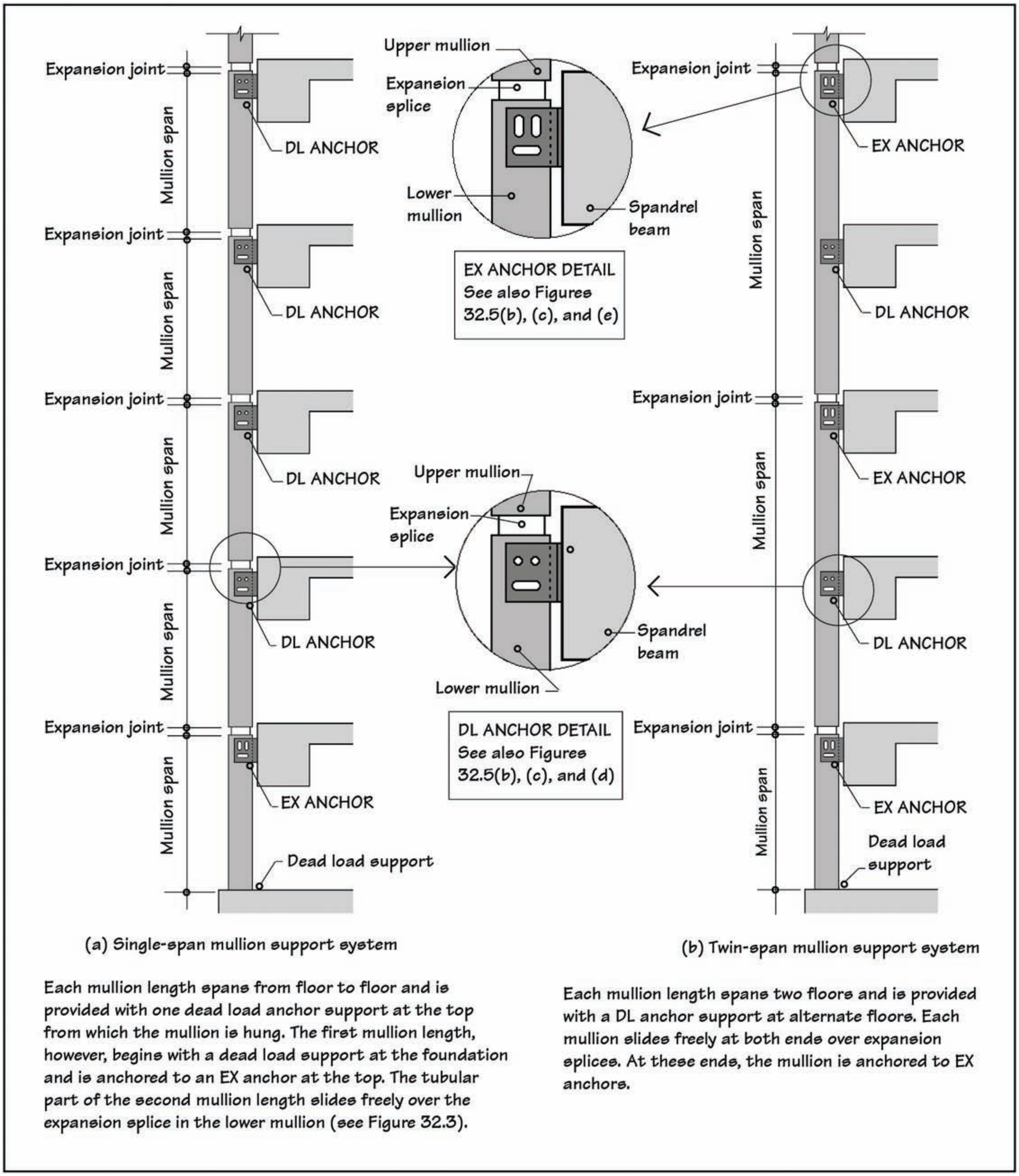

I-shaped expansion splice is inserted into the tubular part of lower mullion and fastened to it. Tubular part of upper mullion length slides freely over the splice with a snug fit. A gap is left between the two mullions for movement, as shown in the lower photograph. See also Figures 32.4, 32.5(b), and (c).
Lower mullion length
Plastic shim separates steel washer from the aluminum mullion to prevent galvanic reaction between steel and aluminum
Mullion anchor, see Figure 32.5(a)
Top of spandrel beam
Upper mullion length
Expansion joint between upper and lower mullion lengths. The width of this joint must be determined based on the creep in columns (if any), deflection of spandrel beam and the thermal movement of mullion length.
Face of spandrel beam
Lower mullion length

FIGURE 32.3 A typical expansion joint between two mullion lengths.

In a twin-span mullion system, the mullions extend over two floors. Because a mullion can have only one dead-load support, DL anchors are provided at alternate floors, Figure 32.4(b). Another difference between a single-span and a twin-span system is that in a twin-span system, expansion anchors (or, simply, *EX anchors*) are also required at alternate floors. In a single-span system, an EX anchor is required only at the second floor of the building.

DL anchors and EX anchors are steel (or aluminum) members to which the mullions are bolted. As shown in Figure 32.4(b), they are almost identical. The only difference between them is that in a DL anchor, the upper pair of holes is round, and in an EX anchor, the upper pair of holes has vertically slotted holes that allow vertical movement.


Expansion joint
Mullion span
DL ANCHOR
Expansion joint
Mullion span
DL ANCHOR
Expansion joint
Mullion span
DL ANCHOR
Expansion joint
Mullion span
DL ANCHOR
Expansion joint
Mullion span
EX ANCHOR
Dead load support
Upper mullion
Expansion splice
Lower mullion
Spandrel beam
EX ANCHOR DETAIL
See also Figures 32.5(b), (c), and (e)
Upper mullion
Expansion splice
Spandrel beam
Lower mullion
DL ANCHOR DETAIL
See also Figures 32.5(b), (c), and (d)
Expansion joint
EX ANCHOR
Mullion span
DL ANCHOR
Expansion joint
EX ANCHOR
Mullion span
DL ANCHOR
Expansion joint
EX ANCHOR
Mullion span
Dead load support

(a) Single-span mullion support system

Each mullion length spans from floor to floor and is provided with one dead load anchor support at the top from which the mullion is hung. The first mullion length, however, begins with a dead load support at the foundation and is anchored to an EX anchor at the top. The tubular part of the second mullion length slides freely over the expansion splice in the lower mullion (see Figure 32.3).

(b) Twin-span mullion support system

Each mullion length spans two floors and is provided with a DL anchor support at alternate floors. Each mullion slides freely at both ends over expansion splices. At these ends, the mullion is anchored to EX anchors.

FIGURE 32.4 Support systems for single-span and twin-span curtain wall mullions. Observe that each mullion has only one dead-load support.

ANCHORING A MULLION TO A DL OR EX ANCHOR

Figure 32.5 shows the anchorage details of a mullion to a DL anchor and an EX anchor. Anchoring a mullion to a DL anchor (or an EX anchor) is a two-step process. The first step includes providing a temporary connection between the mullion and the anchor, Figure 32.5(b). After all mullion lengths are correctly aligned, a permanent connection between the mullion and the anchor is made.

A permanent connection requires field drilling into the mullion through predrilled holes in the anchors, Figures 32.5(c) to (e). Predrilled holes in anchors provide for field adjustment to cater to the (allowed) dimensional variations in the structural frame of the building.

As with other curtain walls (precast concrete, GFRC, natural stone, etc.), the anchorage system of a glass curtain wall to the building's structure is typically provided by the curtain wall's manufacturer. The installation of the wall is generally done by the manufacturer's own installation crew or by an approved third-party installer. For some simple curtain walls that utilize a manufacturer's standard sections, an installer may provide all detailing assistance to the architect.

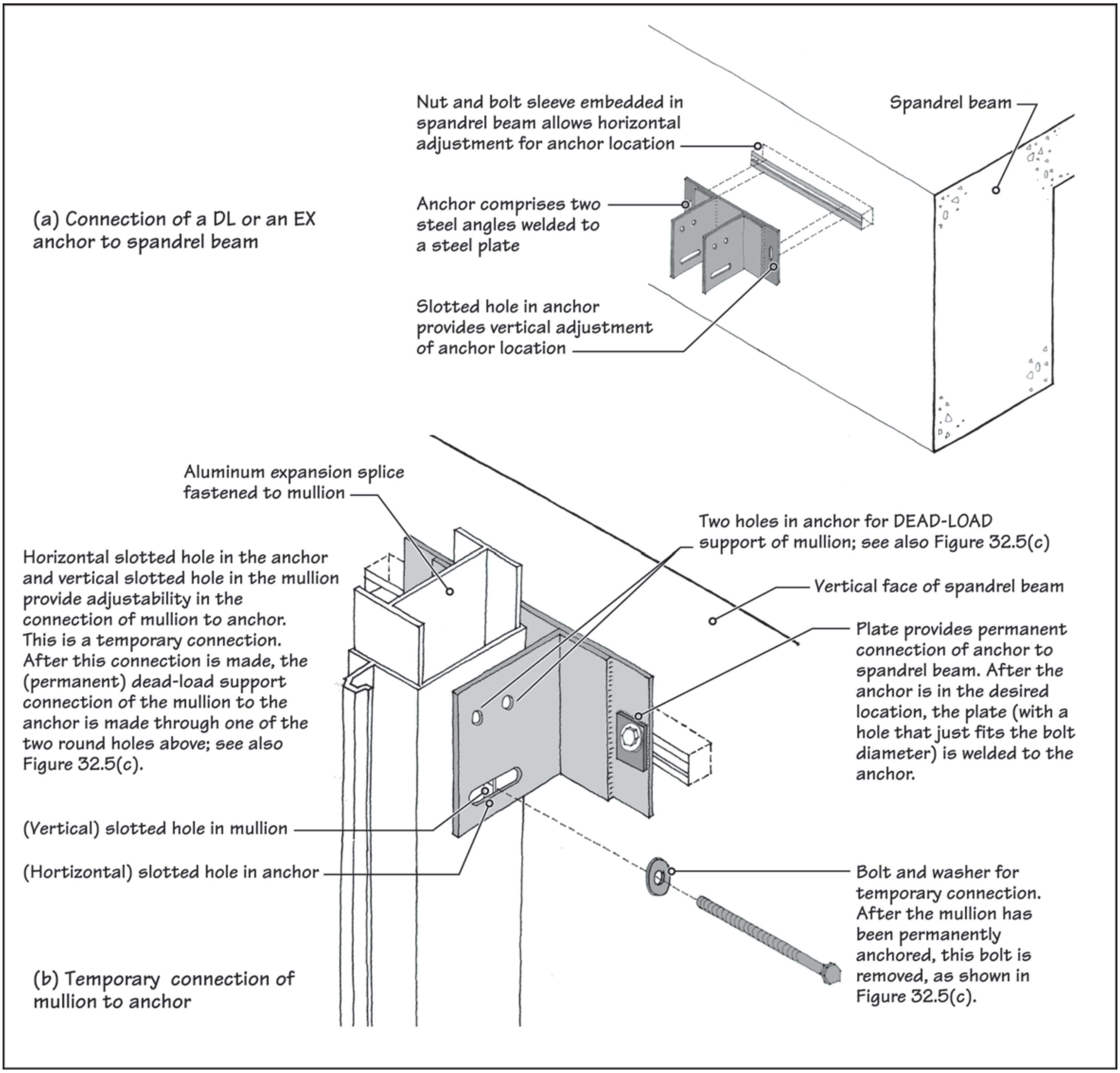
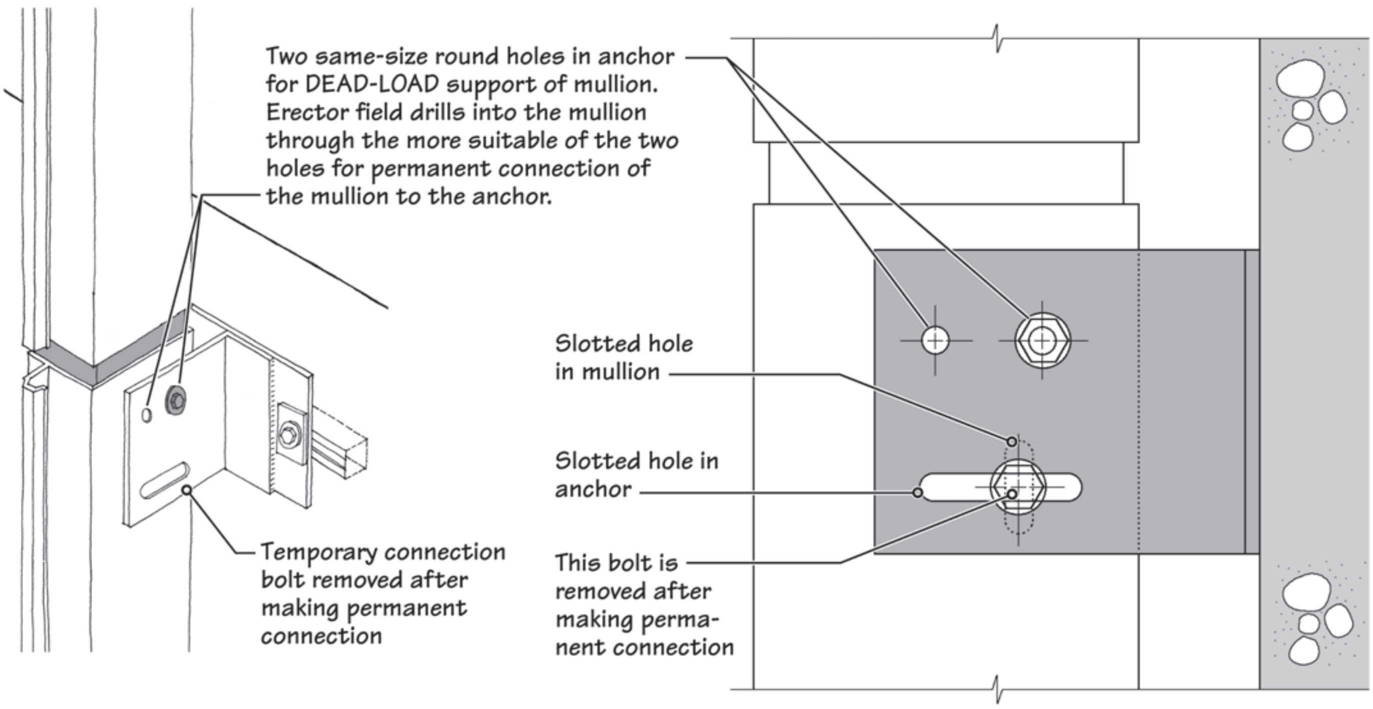
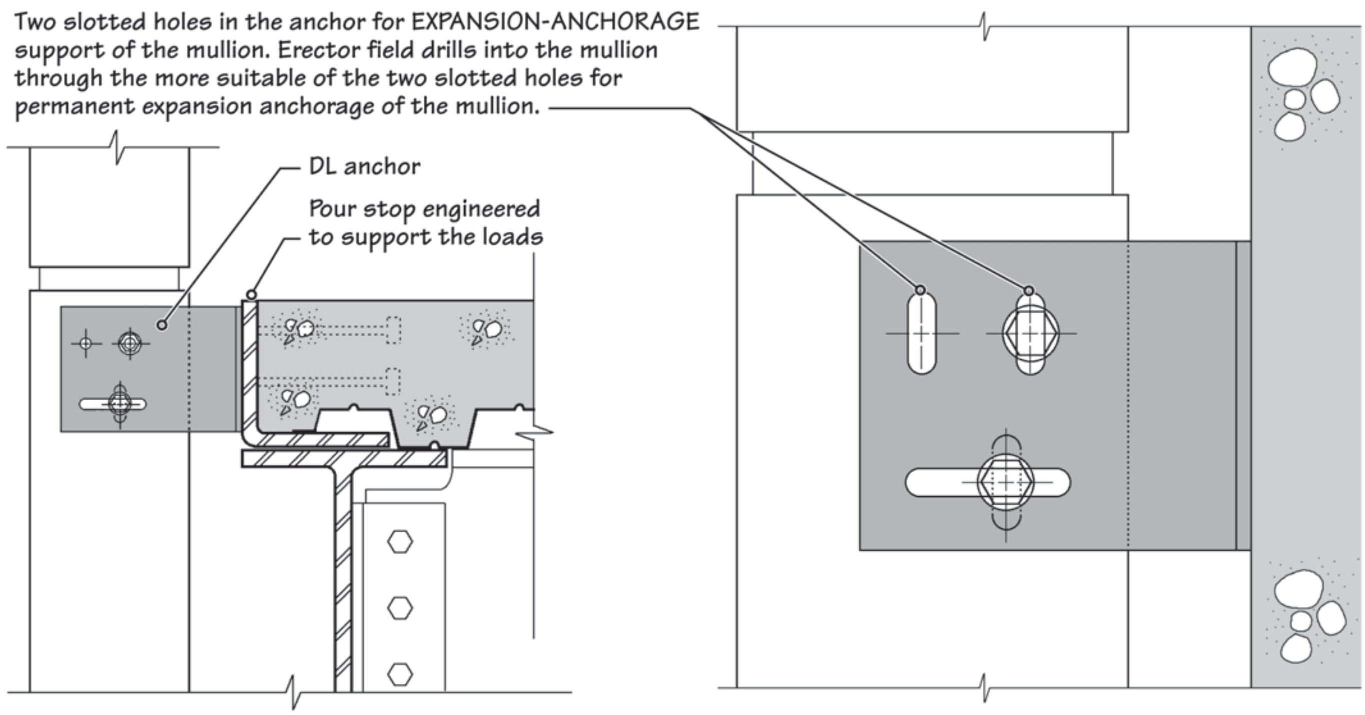

Nut and bolt sleeve embedded in spandrel beam allows horizontal adjustment for anchor location
Spandrel beam
(a) Connection of a DL or an EX anchor to spandrel beam
Anchor comprises two steel angles welded to a steel plate
Slotted hole in anchor provides vertical adjustment of anchor location
Aluminum expansion splice fastened to mullion
Horizontal slotted hole in the anchor and vertical slotted hole in the mullion provide adjustability in the connection of mullion to anchor. This is a temporary connection. After this connection is made, the (permanent) dead-load support connection of the mullion to the anchor is made through one of the two round holes above; see also Figure 32.5(c).
Two holes in anchor for DEAD-LOAD support of mullion; see also Figure 32.5(c)
Vertical face of spandrel beam
Plate provides permanent connection of anchor to spandrel beam. After the anchor is in the desired location, the plate (with a hole that just fits the bolt diameter) is welded to the anchor.
(Vertical) slotted hole in mullion
(Hortizontal) slotted hole in anchor
Bolt and washer for temporary connection. After the mullion has been permanently anchored, this bolt is removed, as shown in Figure 32.5(c).
(b) Temporary connection of mullion to anchor

FIGURE 32.5 Typical anchorage details of a mullion to a spandrel beam.


Two same-size round holes in anchor for DEAD-LOAD support of mullion. Erector field drills into the mullion through the more suitable of the two holes for permanent connection of the mullion to the anchor.
Slotted hole in mullion
Slotted hole in anchor
This bolt is removed after making permanent connection
Temporary connection bolt removed after making permanent connection

(c) Dead-load anchor support of mullion to a reinforced-concrete spandrel beam


Two slotted holes in the anchor for EXPANSION-ANCHORAGE support of the mullion. Erector field drills into the mullion through the more suitable of the two slotted holes for permanent expansion anchorage of the mullion.
DL anchor
Pour stop engineered to support the loads

(d) Dead-load support of mullion to a steel spandrel beam

(e) Expansion-anchor support of mullion to a reinforced-concrete spandrel beam

FIGURE 32.5 (*Continued*) Typical anchorage details of a mullion to a spandrel beam.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. A stick-built glass curtain wall consists of
- **a.** mullions and glass.
- **b.** rails and glass.
- **c.** mullions, rails, and glass.
- **d.** mullions, rails, and preassembled units.
- **e.** preassembled units and glass.

2. A unitized glass curtain wall consists of
- **a.** mullions and glass.
- **b.** rails and glass.
- **c.** mullions, rails, and glass.
- **d.** mullions, rails, and preassembled units.
- **e.** preassembled units and glass.

3. Glass curtain walls in which aluminum framing sections are specially profiled for a particular project are
- **a.** rare because of the prohibitive cost of manufacturing custom profiles.
- **b.** uncommon because of the extremely high cost of manufacturing custom profiles.
- **c.** not uncommon because the cost of custom profiles can be recovered from a few repeat mid-sized to large projects.
- **d.** fairly common because the cost of custom profiles can be recovered from one large project.

4. In a stick-built glass curtain wall, the mullions are typically spaced at
- **a.** 2 ft to 4 ft on center.
- **b.** 4 ft to 6 ft on center.
- **c.** 6 ft to 10 ft on center.
- **d.** 10 ft to 15 ft on center.
- **e.** as needed for the project.

5. In a stick-built glass curtain wall, the rails are typically spaced at
- **a.** 2 ft to 4 ft o.c.
- **b.** 4 ft to 6 ft o.c.
- **c.** 6 ft to 10 ft o.c.
- **d.** 10 ft to 15 ft o.c.
- **e.** as needed for the project.

6. A stick-built glass curtain wall is anchored to the building's structure through
- **a.** mullions.
- **b.** rails.
- **c.** both mullions and rails.
- **d.** none of the above.

7. In a single-span mullion system for a glass curtain wall,
- **a.** one dead-load anchor is provided at every floor level.
- **b.** two dead-load anchors are provided at every floor level.
- **c.** one dead-load anchor is provided at every alternate floor level.
- **d.** two dead-load anchors are provided at every alternate floor level.
- **e.** only one dead-load anchor is provided for the entire height of the wall.

8. In a twin-span mullion system for a glass curtain wall,
- **a.** one dead-load anchor is provided at every floor level.
- **b.** two dead-load anchors are provided at every floor level.
- **c.** one dead-load anchor is provided at every alternate floor level.
- **d.** two dead-load anchors are provided at every alternate floor level.
- **e.** only one dead-load anchor is provided for the entire height of the wall.

9. In a single-span mullion system for a glass curtain wall,
- **a.** one expansion anchor is provided at every floor level.
- **b.** two expansion anchors are provided at every floor level.
- **c.** one expansion anchor is provided at every alternate floor level.
- **d.** two expansion anchors are provided at every alternate floor level.
- **e.** only one expansion anchor is provided for the entire height of the wall.

10. In a twin-span mullion system for a glass curtain wall,
- **a.** one expansion anchor is provided at every floor level.
- **b.** two expansion anchors are provided at every floor level.
- **c.** one expansion anchor is provided at every alternate floor level.
- **d.** two expansion anchors are provided at every alternate floor level.
- **e.** only one expansion anchor is provided for the entire height of the wall.

11. The width of an expansion joint between adjacent mullion lengths in a typical stick-built glass curtain wall
- **a.** is generally 1 in. standard.
- **b.** is generally $\frac{1}{2}$ in. standard.
- **c.** is generally $\frac{1}{4}$ in. standard.
- **d.** is generally $\frac{1}{16}$ in. standard.
- **e.** must be determined on a project-by-project basis.

32.3 STICK-BUILT GLASS CURTAIN WALL DETAILS

After the mullions have been anchored to the structural frame, the remaining items in the wall's erection require

- Connection of the rails to the mullions
- Installation of the glass.

RAIL-TO-MULLION CONNECTION

Manufacturers use various methods to connect the rails to the mullions. A commonly used method involves short aluminum extrusions, called *shear blocks*, which are fastened to the mullions with screws. Subsequently, the rails are snapped over the shear blocks, one shear block at each end of a rail, Figure 32.6. Thus, no fasteners are used between the rail and the shear blocks.

Because the length of each rail is small (4 ft to 6 ft is typical), a fairly small space is required for the expansion or contraction of a rail. In general, the length of a rail is $\frac{1}{16}$ in. less than the clear distance between mullions.

OUTSIDE-GLAZED AND INSIDE-GLAZED CURTAIN WALLS

One of the factors that determines the cross-sectional shapes of mullions and rails is whether the glass in the wall is to be installed from the outside or the inside of the building, referred to, respectively, as:

- Outside-glazed curtain walls
- Inside-glazed curtain walls

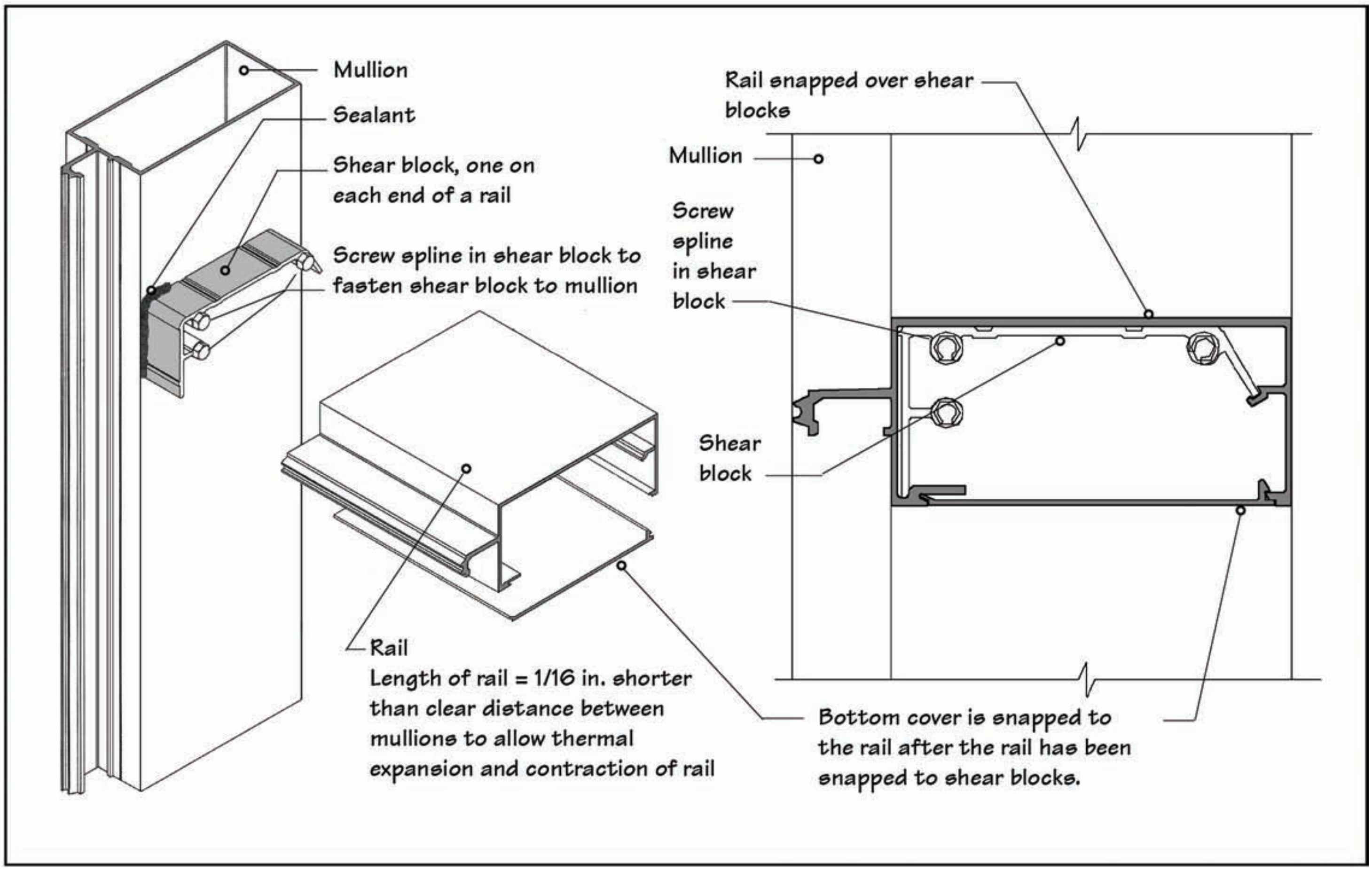

Mullion
Sealant
Shear block, one on each end of a rail
Screw spline in shear block to fasten shear block to mullion
Rail
Length of rail = 1/16 in. shorter than clear distance between mullions to allow thermal expansion and contraction of rail
Rail snapped over shear blocks
Mullion
Screw spline in shear block
Shear block
Bottom cover is snapped to the rail after the rail has been snapped to shear blocks.

FIGURE 32.6 Typical connection between rails and mullions of a stick-built glass curtain wall.

In an *outside-glazed* wall, the glass panes are installed from the outside of the building by workers standing on a scaffold or staging. This method of installing glass is less efficient and more expensive due to the cost of scaffolding or staging. It is generally used for low- to mid-rise buildings. The glass in an outside-glazed wall can be secured in two ways:

- Pressure plate–captured glass (Figures 32.7 to 32.9)
- Structural silicone sealant–adhered glass (Figure 32.10)

In an *inside-glazed* wall, the glass is installed by workers standing on the appropriate floor of the building. The system is more efficient because it does not require scaffolding or staging. It is the system of choice for high-rise buildings. However, the cross-sectional shapes of mullions and rails for the inside-glazed system are more complex than the corresponding shapes for the outside-glazed system.

OUTSIDE-GLAZED WALLS (PRESSURE PLATE–CAPTURED GLASS)

In an outside-glazed curtain wall, the glass is held by horizontal and vertical pressure plates, which are fastened to the mullions and rails with screws. A plastic insert is used between the pressure plate and the mullion (or the rail), which functions as a thermal separator. The pressure plates are finally covered with snap-on covers, Figure 32.7.

Because the covers are the only external visible part of the curtain wall framing, they have a major influence on the curtain wall appearance. They can be profiled in various colors and shapes, and can be custom-made for medium- to large-size projects without adding greatly to the project's cost.

The exterior and interior gaskets should prevent water from leaking through the wall. However, a curtain wall system typically includes accommodations for the drainage of water, should it penetrate beyond the gaskets. This is accomplished through drainage weep holes in the pressure plates and the covers. Thus, in a typical curtain wall, each glass-pane frame is drained independently. Figure 32.9 shows typical sections through a pressure plate–captured outside-glazed curtain wall.

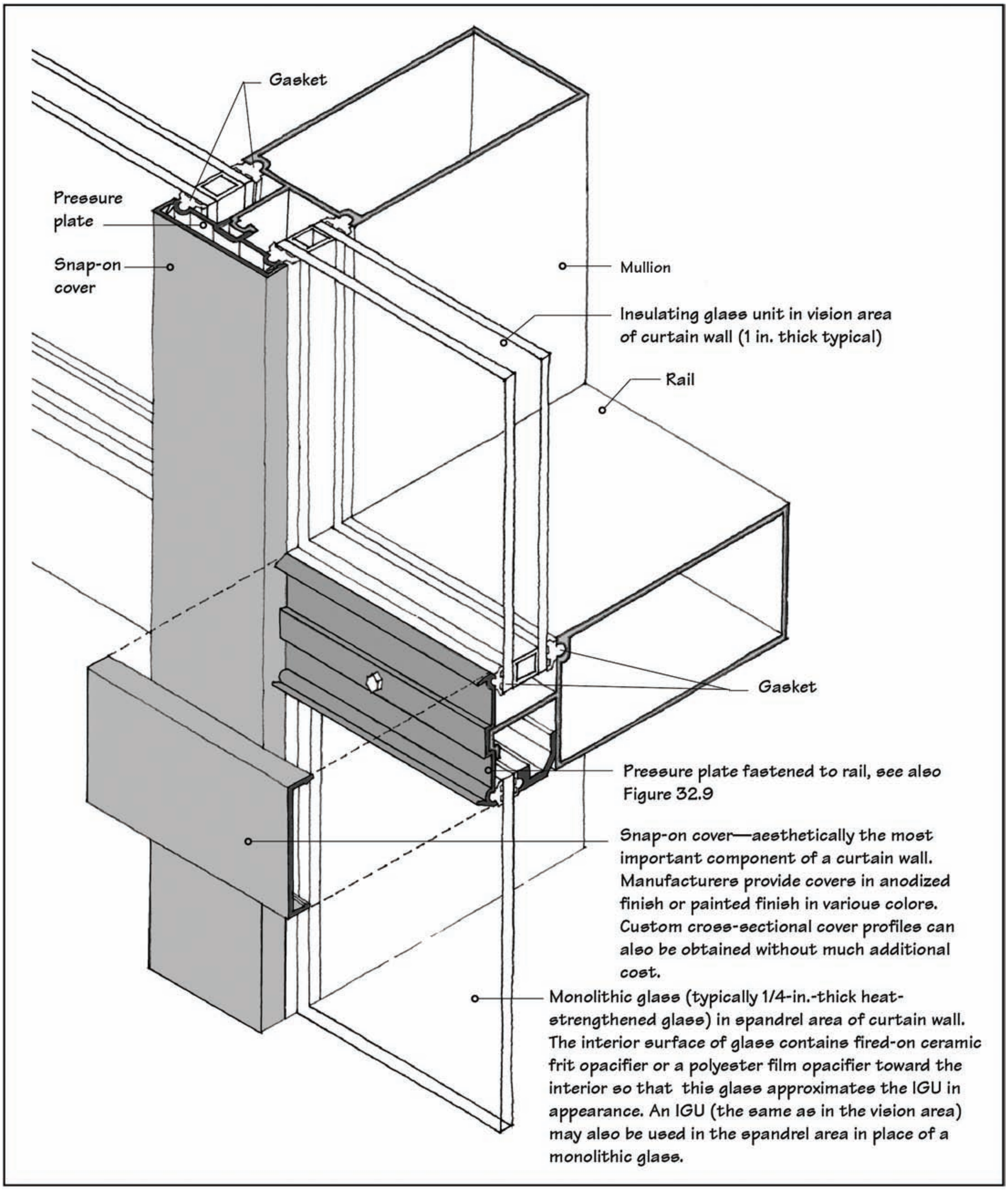

Gasket
Pressure plate
Snap-on cover
Mullion
Insulating glass unit in vision area of curtain wall (1 in. thick typical)
Rail
Gasket
Pressure plate fastened to rail, see also Figure 32.9
Snap-on cover—aesthetically the most important component of a curtain wall. Manufacturers provide covers in anodized finish or painted finish in various colors. Custom cross-sectional cover profiles can also be obtained without much additional cost.
Monolithic glass (typically 1/4-in.-thick heat-strengthened glass) in spandrel area of curtain wall. The interior surface of glass contains fired-on ceramic frit opacifier or a polyester film opacifier toward the interior so that this glass approximates the IGU in appearance. An IGU (the same as in the vision area) may also be used in the spandrel area in place of a monolithic glass.

FIGURE 32.7 Anatomy of an outside-glazed glass curtain wall (pressure plate–captured glass).

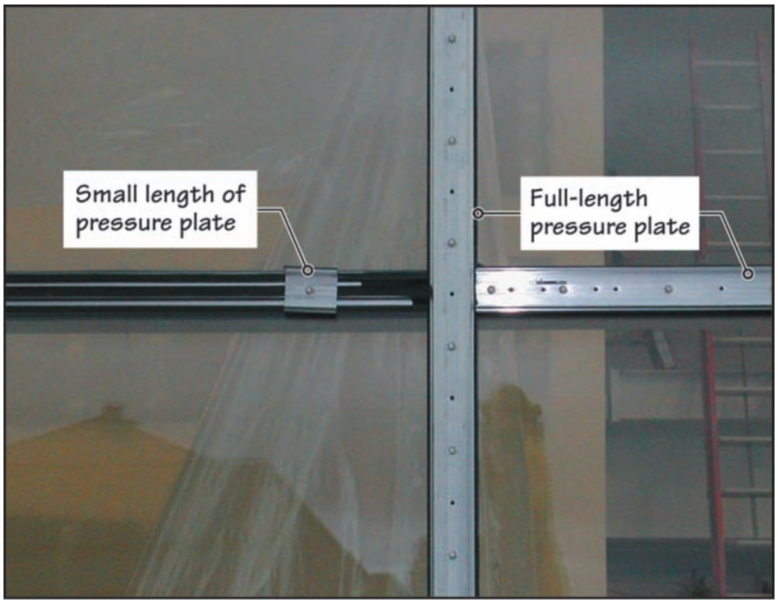

Small length of pressure plate
Full-length pressure plate

FIGURE 32.8 In fastening the pressure plates to curtain wall framing members, the glass is temporarily held by small pressure plate members. After several glass panes are in position, the temporary pressure plates are removed and replaced by full-length pressure plates.

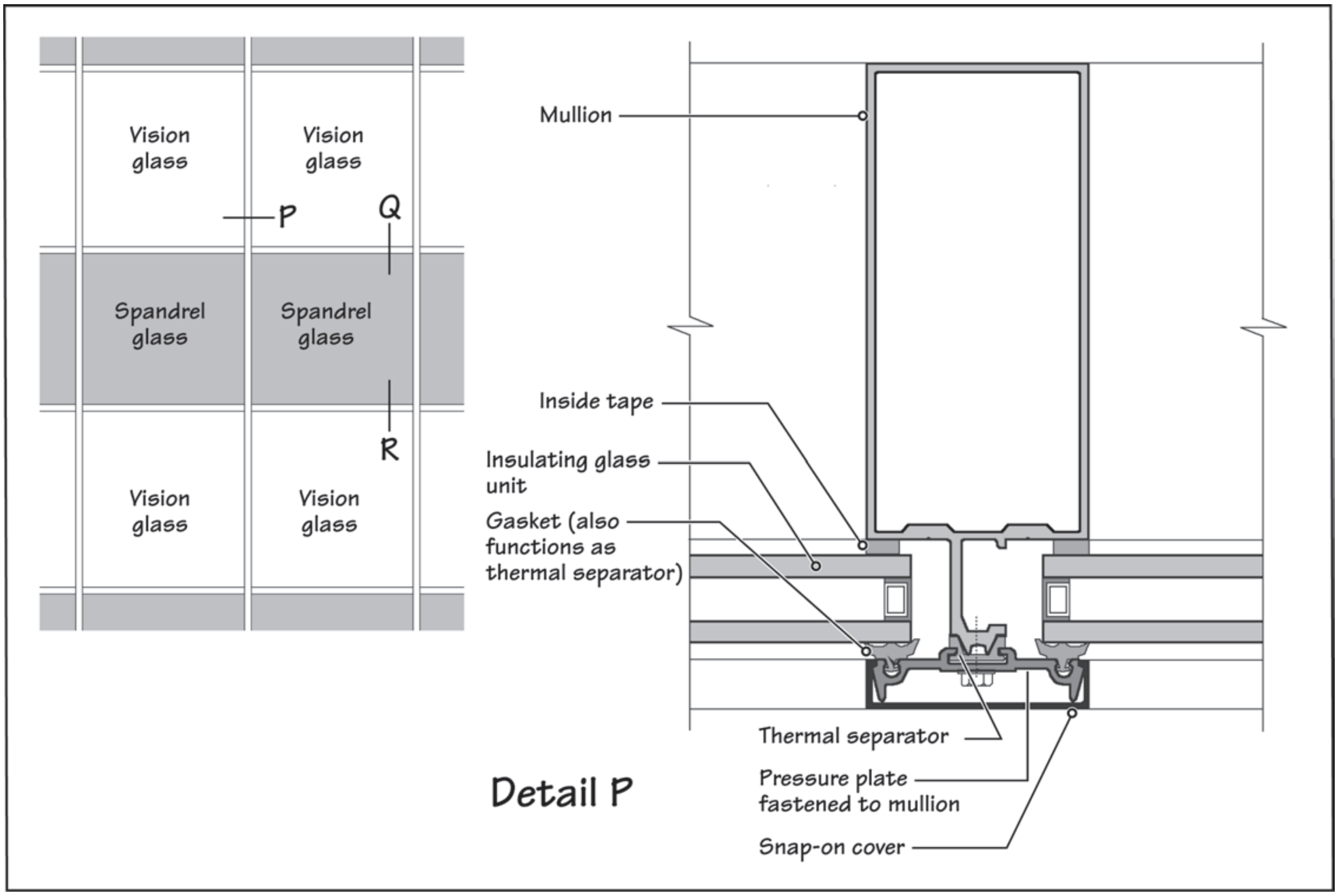

Vision glass
Vision glass
P
Q
Spandrel glass
Spandrel glass
R
Vision glass
Vision glass
Mullion
Inside tape
Insulating glass unit
Gasket (also functions as thermal separator)
Thermal separator
Pressure plate fastened to mullion
Snap-on cover
Detail P

FIGURE 32.9(a) Typical details of an outside-glazed glass curtain wall (pressure plate–captured glass). Aluminum sections used in the details are by Vistawall Architectural Products. Other manufacturers provide similar sections.

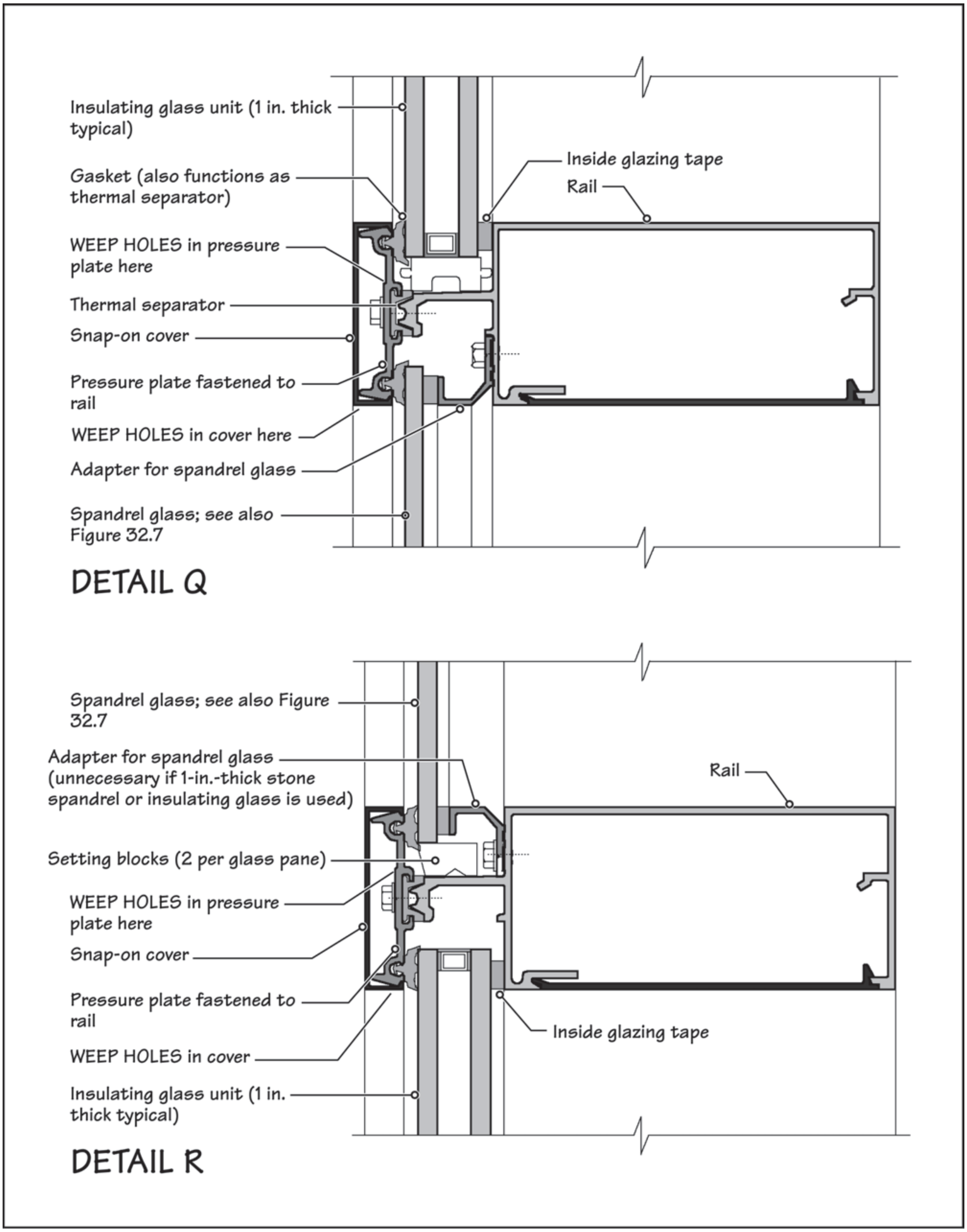

Insulating glass unit (1 in. thick typical)
Inside glazing tape
Rail
Gasket (also functions as thermal separator)
WEEP HOLES in pressure plate here
Thermal separator
Snap-on cover
Pressure plate fastened to rail
WEEP HOLES in cover here
Adapter for spandrel glass
Spandrel glass; see also Figure 32.7
DETAIL Q
Spandrel glass; see also Figure 32.7
Adapter for spandrel glass (unnecessary if 1-in.-thick stone spandrel or insulating glass is used)
Rail
Setting blocks (2 per glass pane)
WEEP HOLES in pressure plate here
Snap-on cover
Pressure plate fastened to rail
Inside glazing tape
WEEP HOLES in cover
Insulating glass unit (1 in. thick typical)
DETAIL R

FIGURE 32.9(b) Typical details of an outside-glazed glass curtain wall (pressure plate–captured glass). Aluminum sections used in the details are by Vistawall Architectural Products. Other manufacturers provide similar sections.

OUTSIDE-GLAZED WALLS (STRUCTURAL SILICONE SEALANT–ADHERED GLASS)

Another version of an outside-glazed curtain wall is one in which the glass is held by structural silicone sealant. In this type of system, the vertical edges of a glass pane are adhered to the mullions with beads of structural silicone sealant. The mullions in this wall are similar to those of an outside-glazed wall without the mullion nose. The horizontal edges of the glass are supported on rails and anchored to them through standard pressure plates, Figure 32.10. The absence of vertical pressure plates in the system accentuates the horizontality of the covers.

INSIDE-GLAZED WALLS

In an inside-glazed wall, pressure plates are not used. Therefore, the aluminum curtain wall sections are different from those used for the outside-glazed wall. These sections include glazing pockets—in both mullions and the bottom rail—of an opening. The top rail of the opening is open and has no glazing pocket. The openness allows the glass to be inserted in the opening. After the glass is inserted, a glazing stop is snapped on the top rail of the opening from the inside. This secures the glass in the opening, Figure 32.11(b).

Figure 32.11(c) shows a plan view of the process of inserting the glass. Other details of an inside-glazed wall are shown in Figures 32.11(a) and (d). An important point to note is that in the inside-glazed wall, the mullion and rail covers must be installed before inserting the glass, Figure 32.12.

DETAILING A MULTISTORY GLASS CURTAIN WALL

Figure 32.13 shows the details of a typical multistory (outside-glazed) glass curtain wall at the floor, sill, and ceiling levels. At the sill level, an aluminum stool provides the interior finish. It is snapped to a continuous clip on one side, and its vertical leg is fastened to a treated wood nailer on the other side.

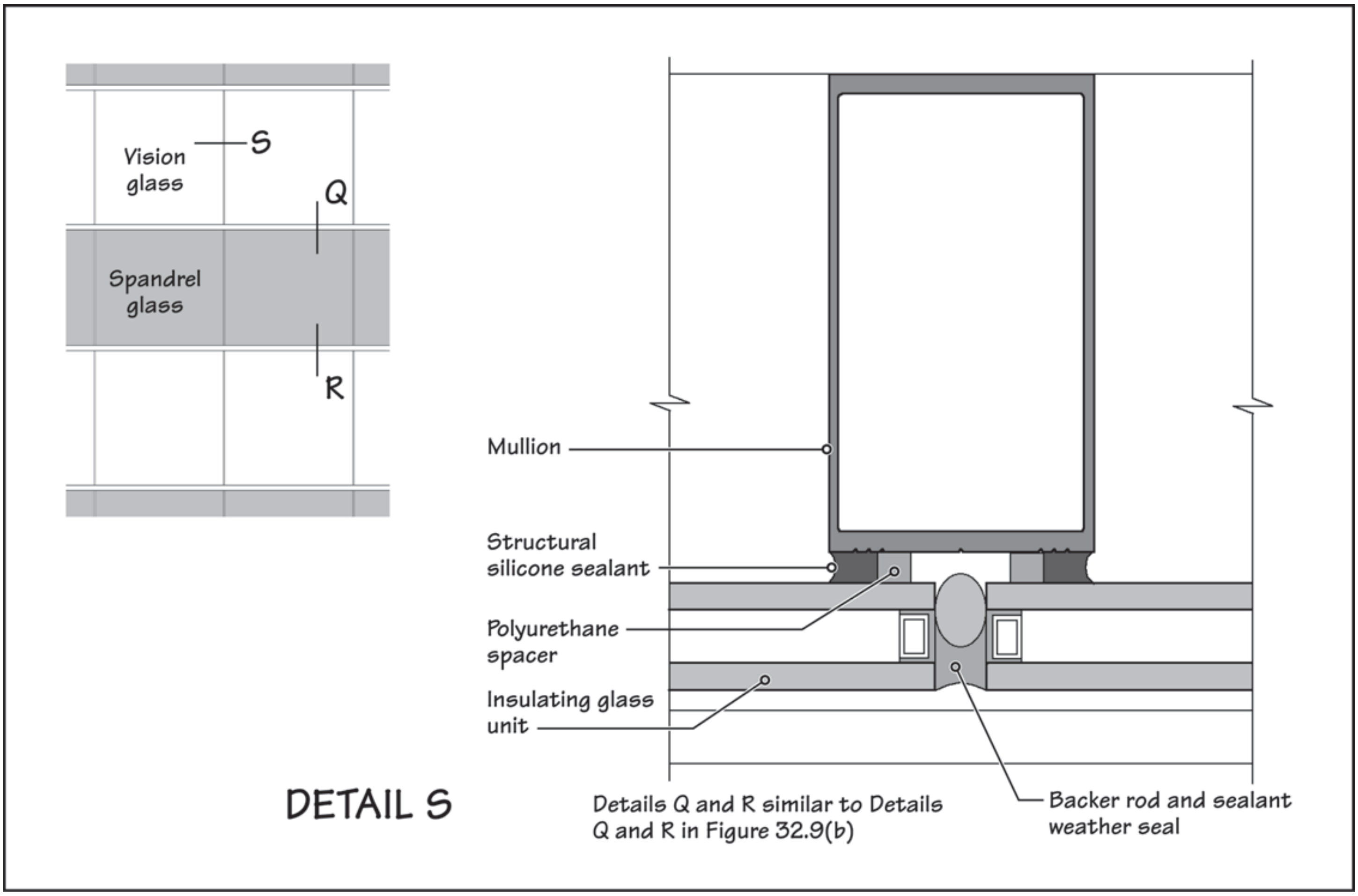
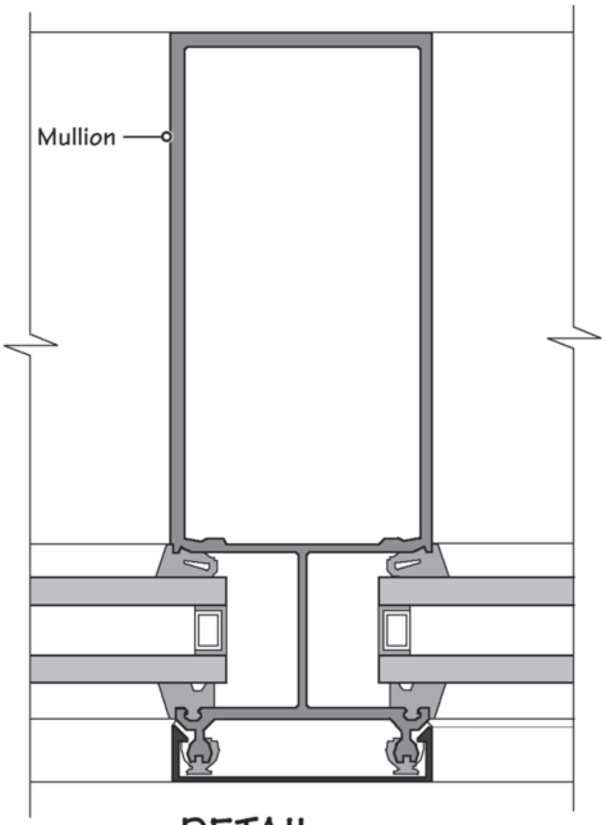
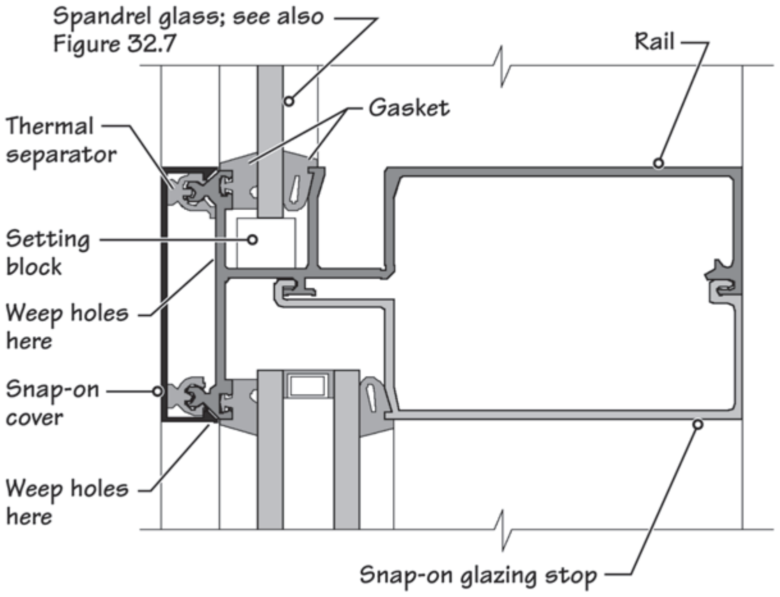

Vision glass
S
Q
Spandrel glass
R
Mullion
Structural silicone sealant
Polyurethane spacer
Insulating glass unit
DETAIL S
Details Q and R similar to Details Q and R in Figure 32.9(b)
Backer rod and sealant weather seal

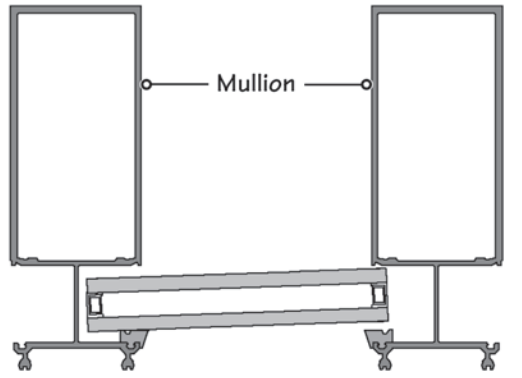
FIGURE 32.10 Typical details of an outside-glazed curtain wall (structural silicone sealant–adhered glass). Aluminum section used in the detail is by Vistawall Architectural Products. Other manufacturers provide a similar section.



(a) **DETAIL** at mullion

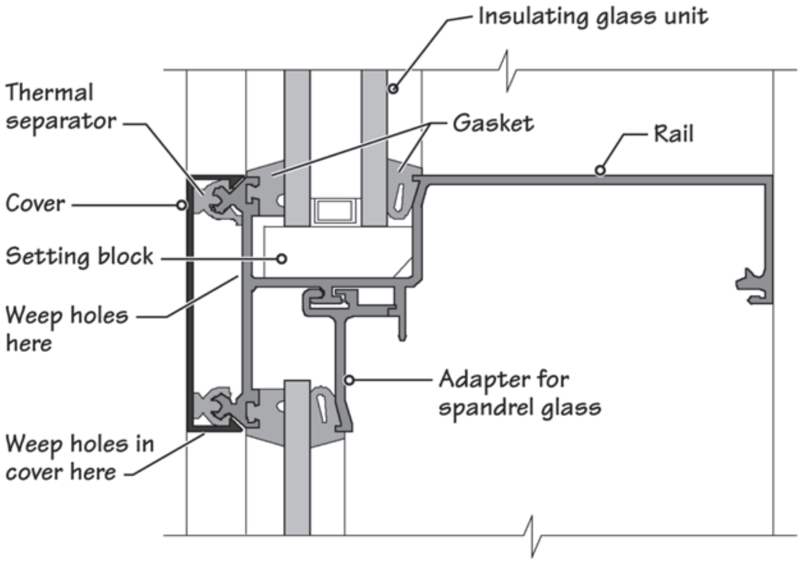

Spandrel glass; see also Figure 32.7
Rail
Thermal separator
Gasket
Setting block
Weep holes here
Snap-on cover
Weep holes here
Snap-on glazing stop

(b) **DETAIL** at ceiling level


Mullion
Mullion

Deep glazing pockets in mullions allow the glass to be inserted from within the building. The open rail at the top of the opening facilitates the insertion. The opening is closed with a glazing stop after the glass is in position; see (b) DETAIL at ceiling level.

(c) **DETAIL** of glass insertion in opening


Insulating glass unit
Thermal separator
Gasket
Rail
Cover
Setting block
Weep holes here
Adapter for spandrel glass
Weep holes in cover here

(d) **DETAIL** at sill level

FIGURE 32.11 Typical details of an inside-glazed curtain wall. Aluminum sections used in the details are by Vistawall Architectural Products. Other manufacturers provide similar sections.

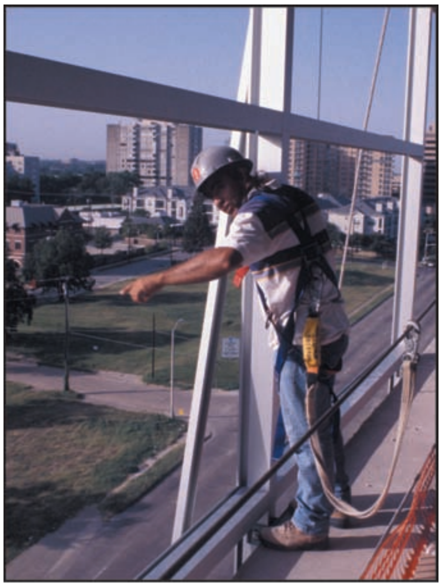


FIGURE 32.12 In an inside-glazed curtain wall, the covers are installed before the glass. In this photo, an installer is installing the snap-on cover on the mullion from an upper floor, and is helped by an installer at the lower floor. In an outside-glazed curtain wall, the covers are generally installed after installation of the glass and pressure plates.

Usually a heat-strengthened glass pane (with a fired-on ceramic frit opacification or a polyester film opacification on the interior surface of the glass to prevent seeing through it) is used in the spandrel area (see Figure 32.7). A fire-containment assembly is generally required to prevent the passage of fire and smoke between the adjacent floors of the building. This assembly consists of semirigid mineral wool insulation pressure-fitted (and supported on metal clips) in the space between the curtain wall and the spandrel beam. To obtain a good seal, the insulation is topped with a liquid-applied, fire-resistive sealant.

In addition to the fire-containment assembly, the entire spandrel area of the curtain wall is provided with mineral wool insulation placed behind the spandrel glass. To prevent condensation between the glass and the insulation, a vapor retarder is provided in this area. This generally consists of an aluminum foil lamination on the insulation's interior face. Where a high degree of condensation potential exists, a metal panel (referred to as a *metal back pan*) should be specified in place of an aluminum foil lamination.

PRACTICE **QUIZ**

Each question has only one correct answer. Select the choice that best answers the question.

12. The width of an expansion joint in the rails of a typical stick-built glass curtain wall
- **a.** is 1 in. standard.
- **b.** is $\frac{1}{2}$ in. standard.
- **c.** is $\frac{1}{4}$ in. standard.
- **d.** is $\frac{1}{32}$ in. standard.
- **e.** must be determined on project-by-project basis.

13. In a stick-built glass curtain wall, the mullions are erected first and the rails are inserted between them.
- **a.** True
- **b.** False

14. A shear block is used
- **a.** at a mullion expansion joint to allow the mullion to move.
- **b.** at the dead-load anchor of a mullion.
- **c.** at the expansion anchor of a mullion.
- **d.** to connect a rail to adjacent mullions.
- **e.** none of the above.

15. A glass curtain wall in which the glass is pressure plate captured is glazed from the
- **a.** building's interior.
- **b.** building's exterior.
- **c.** (a) or (b).

16. As shown in this text, a glass curtain wall in which the glass is structural silicone adhered is glazed from the
- **a.** building's interior.
- **b.** building's exterior.
- **c.** (a) or (b).

17. In a glass curtain wall with pressure plate–captured glass, there are
- **a.** no covers.
- **b.** covers in both horizontal and vertical directions.
- **c.** covers only in the horizontal direction.
- **d.** covers only in the vertical direction.

18. As shown in the text, a glass curtain wall with structural silicone–adhered glass
- **a.** has no exterior covers.
- **b.** has exterior covers in both horizontal and vertical directions.
- **c.** has exterior covers only in the horizontal direction.
- **d.** has exterior covers only in the vertical direction.

19. A typical glass curtain wall is provided with weep holes to drain infiltrating water even though it is sealed from both the inside and the outside with gaskets or tapes.
- **a.** True
- **b.** False

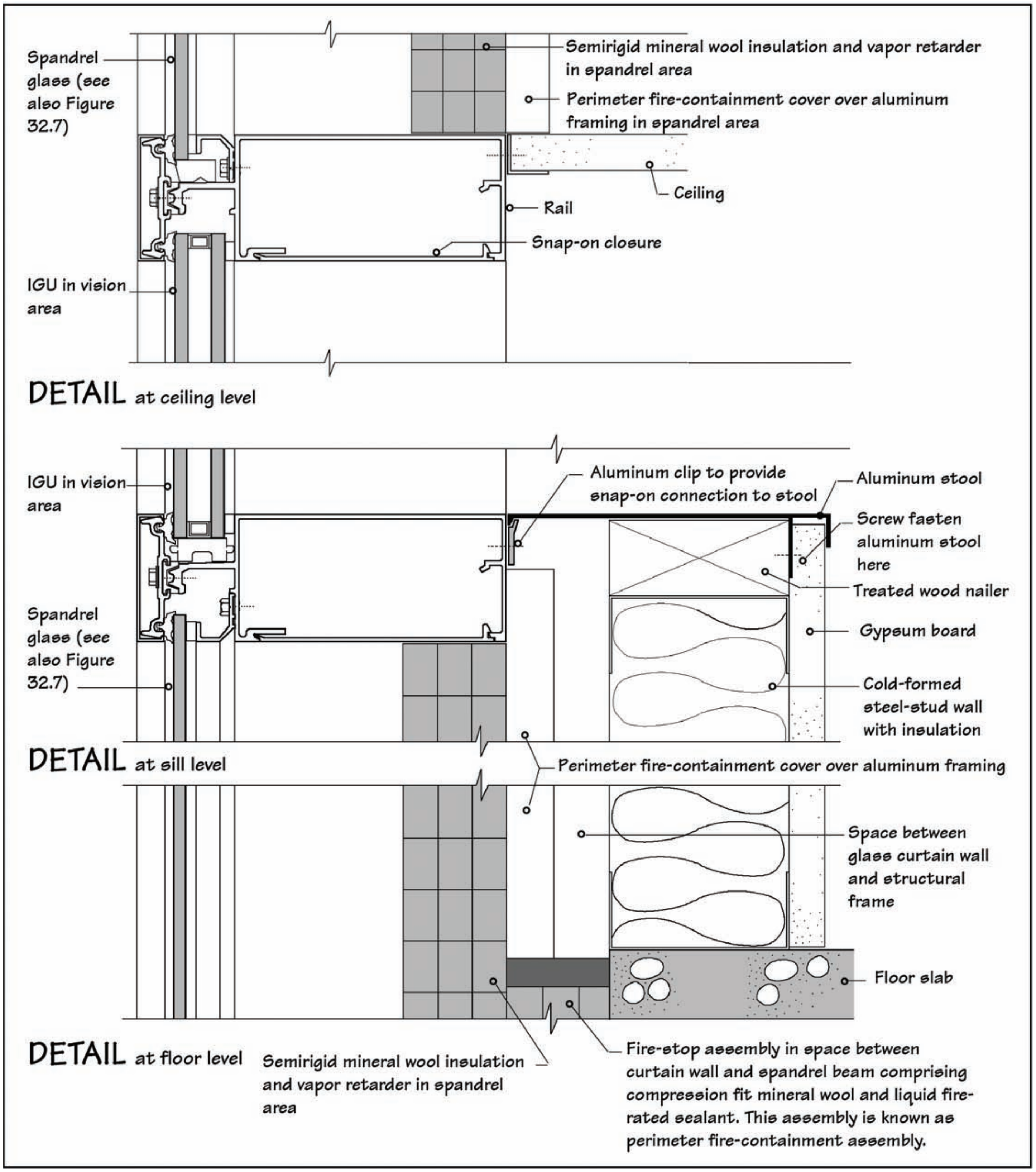
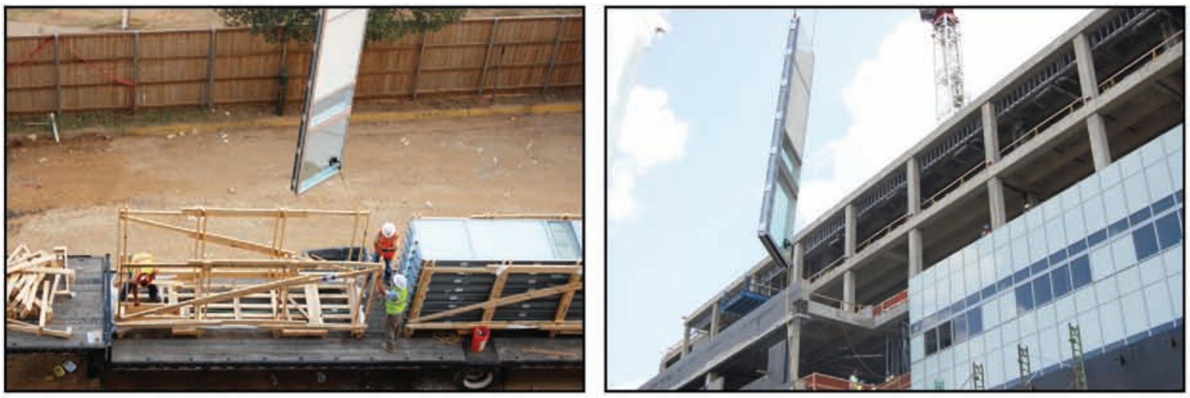

Spandrel glass (see also Figure 32.7)
Semirigid mineral wool insulation and vapor retarder in spandrel area
Perimeter fire-containment cover over aluminum framing in spandrel area
Ceiling
Rail
Snap-on closure
IGU in vision area
DETAIL at ceiling level
IGU in vision area
Aluminum clip to provide snap-on connection to stool
Aluminum stool
Screw fasten aluminum stool here
Treated wood nailer
Gypsum board
Spandrel glass (see also Figure 32.7)
Cold-formed steel-stud wall with insulation
DETAIL at sill level
Perimeter fire-containment cover over aluminum framing
Space between glass curtain wall and structural frame
Floor slab
DETAIL at floor level
Semirigid mineral wool insulation and vapor retarder in spandrel area
Fire-stop assembly in space between curtain wall and spandrel beam comprising compression fit mineral wool and liquid fire-rated sealant. This assembly is known as perimeter fire-containment assembly.

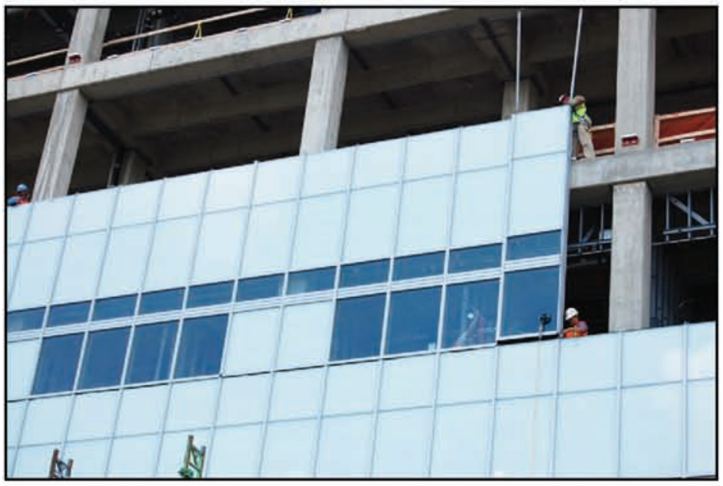
FIGURE 32.13 Typical floor level, sill level, and ceiling level details of an outside-glazed glass curtain wall. Note the fire-stopping in the space between the spandrel beam and the curtain wall.

32.4 UNITIZED GLASS CURTAIN WALL

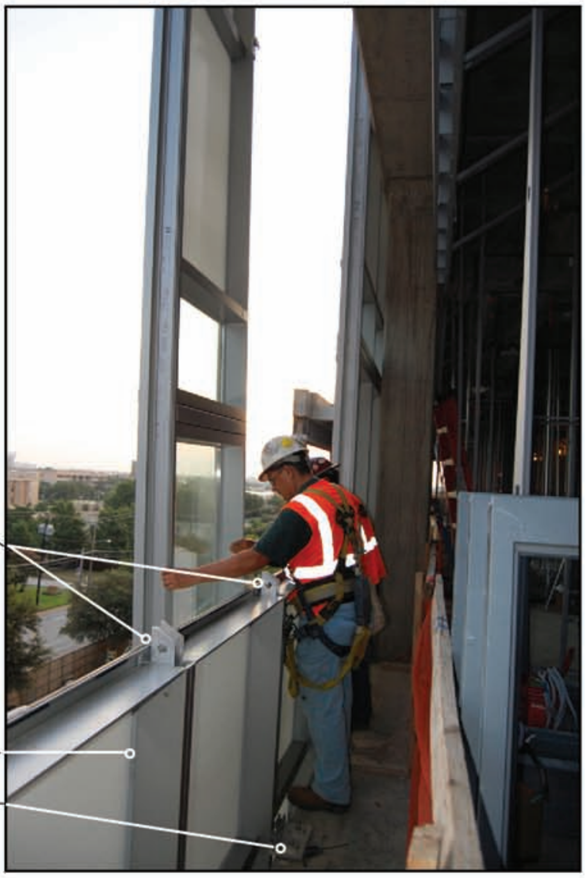
As shown in Figure 32.1(b), in a unitized glass curtain wall, the wall units are preassembled (and generally preglazed) in a fabrication shop and brought to the site for installation, so that the wall is assembled at the site, unit by unit, instead of assembling sticks of mullions and rails. Figures 32.14(a) to (d) show the important steps in the installation of a typical unitized wall to a building structure.

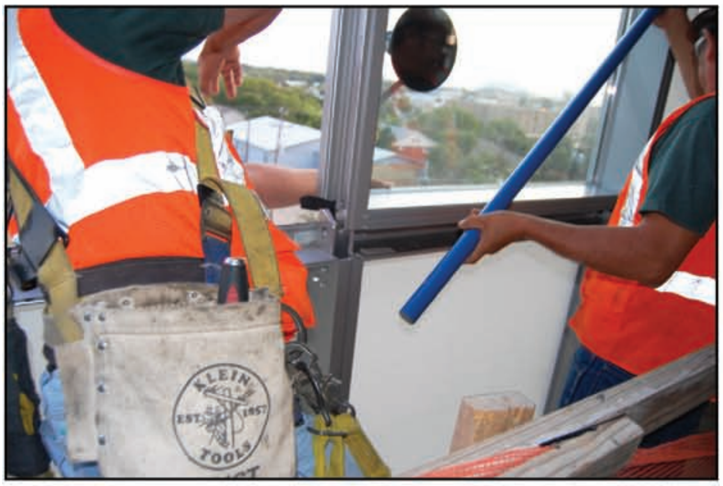


(a) Using a crane, unitized cutain wall elements are carried up from the delivery truck to the building facade.

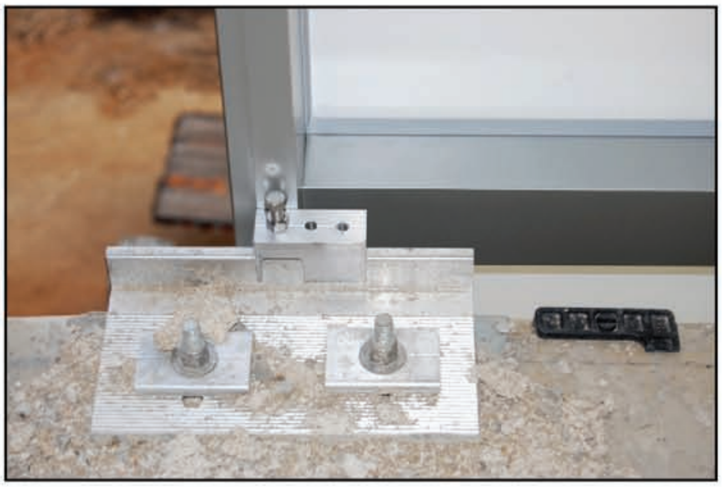


(b) The new unit is installed by placing both its mulions over the (projecting) splices in the lower unit. The splices function as expansion splices (see Figure 32.3) and also provide lateral load support to the unit. The lower unit is anchored to the floor structure through a dead load support to the unit.


Projecting splices (one on each side of the lower unit) function as expansion splices and also as lifting elements. Observe holes in splices to which lifting cables are attached.
Unit already installed
Dead load anchor for the unit here, see (d) below



(c) The new unit being forced over the (projecting) splice



(d) Anchorage of unit to the floor structure, providing a dead load support

FIGURE 32.14 Installation of a unitized curtain wall element.

The units are designed to mate with the adjacent units at the mullions, and at the top and bottom rails. The bottom rail of the upper unit connects to the top rail of the lower unit. As shown in Figure 32.14(b), the splices projecting from the top rail of the lower unit fit snugly into the void in the bottom rail of the upper unit. This detail provides the lateral-load resistance and is similar to the detail used in a stick-built wall (see Figure 32.3). The dead-load resistance of the unit is provided through its anchorage to the floor, Figure 32.14(d). Two adjacent units generally share the same dead-load anchorage.

32.5 STRUCTURAL PERFORMANCE OF A GLASS-ALUMINUM WALL

The most important structural requirement of a glass-aluminum wall is its ability to resist lateral loads (particularly wind loads), including missile-impact resistance in hurricane-prone regions. Just as the design of a glass-aluminum wall's anchorage to the structure is accomplished by the wall manufacturer (or installer, see Section 32.2), its lateral-load-resistance design is also provided by the manufacturer (or installer) based on the lateral-load intensities provided by the project architect or structural engineer.

Manufacturers generally have several standard sections designed to suit various lateral-load intensities. For high lateral-load intensities, a strategy often used is to enclose structural steel (or aluminum) sections within the mullions, Figure 32.15. The enclosed steel sections and the mullions are fastened together to produce a composite action between them. Structural C- or I-sections are commonly used as enclosed sections. Channels provide the advantage of nesting, so that two or three channels may be used within the same mullion. The enclosed steel sections are suitably coated to prevent galvanic action between the aluminum and the steel.

An alternative to enclosed steel sections is to anchor the mullions to an independent steel structural frame, Figure 32.16. This strategy is generally used in a tall glass-aluminum wall where the mullions do not have intermediate supports to reduce their span, such as those provided by the floor structure in a multistory curtain wall.

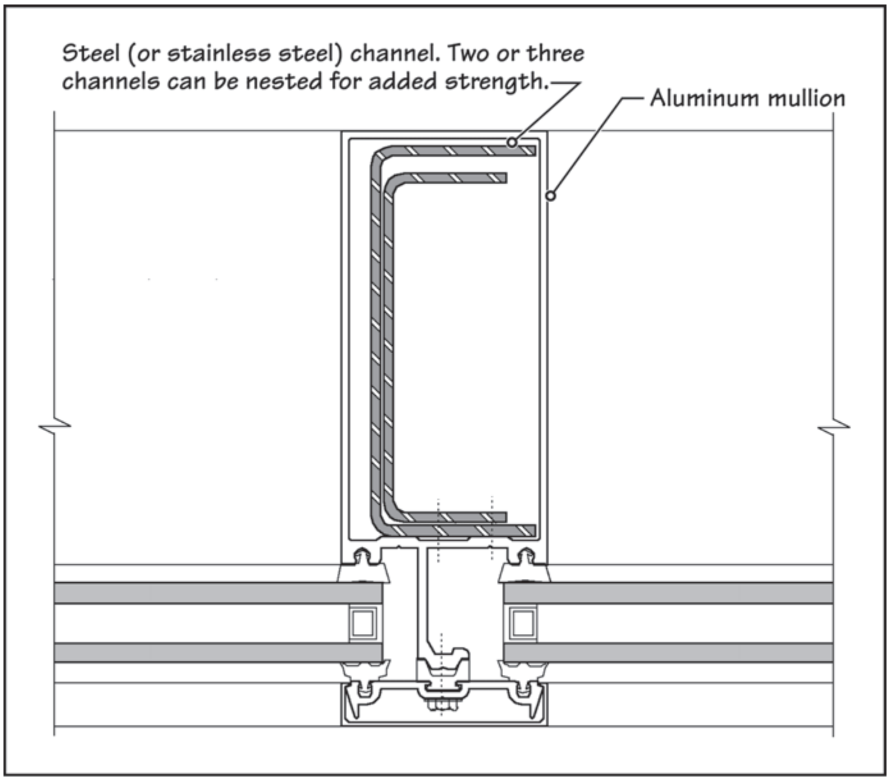
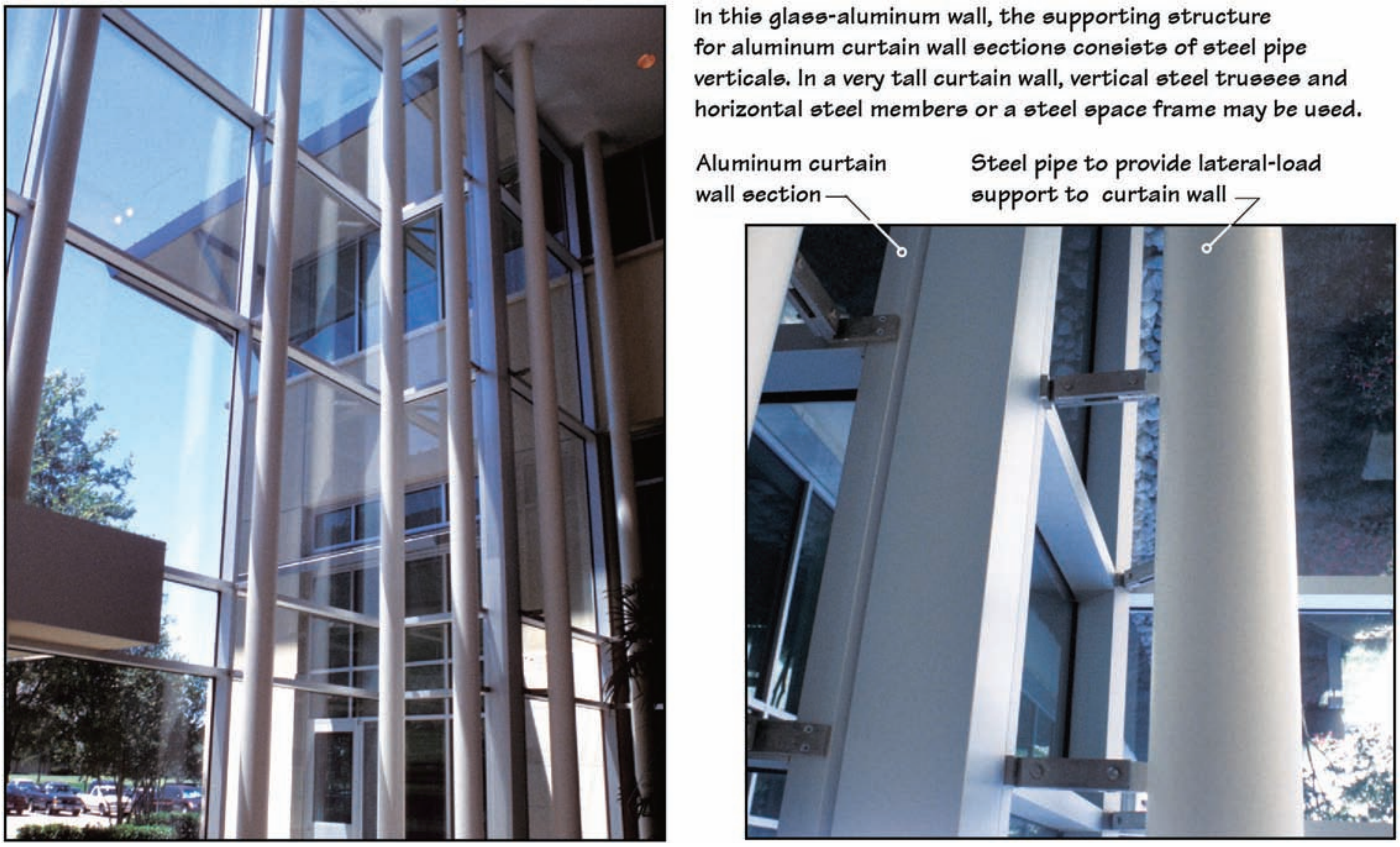

Steel (or stainless steel) channel. Two or three channels can be nested for added strength.
Aluminum mullion

FIGURE 32.15 One of the ways to increase the lateral-load resistance of aluminum mullions is to enclose structural steel sections within them.


Aluminum curtain wall section
Steel pipe to provide lateral-load support to curtain wall

In this glass-aluminum wall, the supporting structure for aluminum curtain wall sections consists of steel pipe verticals. In a very tall curtain wall, vertical steel trusses and horizontal steel members or a steel space frame may be used.

FIGURE 32.16 A tall glass wall with standard curtain wall sections anchored to an interior structural steel vertical member to provide lateral-load support to aluminum mullions. In this building, a steel pipe support is used. In taller walls, vertical steel trusses are common.

32.6 ENVIRONMENTAL PERFORMANCE CRITERIA FOR A GLASS CURTAIN WALL

The nonstructural performance of a glass curtain wall is just as important as its structural performance. Among the important nonstructural design criteria for a glass curtain wall are:

- Air-infiltration control
- Rainwater- and meltwater-penetration control
- U-value
- Solar heat gain
- Condensation resistance
- Vapor diffusion
- Sound transmission
- Hurricane resistance
- Seismic resistance
- Thermal and structural movement
- Glass-cleaning-equipment load

For standard curtain walls, manufacturers provide the values for these criteria based on the tests conducted by recognized third-party laboratories. For custom walls, technical design support is generally available from the manufacturers. For a complicated wall design, the architect may need additional help from a curtain wall design consultant and a specialized testing laboratory to determine the wall's performance.

AIR-INFILTRATION CONTROL

In the United States, the maximum air infiltration allowed through a glass curtain wall is typically 0.06 cfm/ft^2 under an inside-outside air pressure difference of 1.57 psf. In Canada, the requirement is three times more stringent—that is, 0.02 cfm/ft^2 under an air pressure difference of 1.57 psf.

Where lower air infiltration is required, curtain wall systems, which provide a rate of up to 0.01 cfm/ft^2 under an inside-outside air pressure difference of 6.24 psf, are available.

NOTE

cfm is an acronym for cubic feet per minute.

(Note that a 1.57-psf air pressure difference is equivalent to that exerted by a wind speed of 25 mph. Similarly a 6.24-psf air pressure difference is equivalent to that created by a 50-mph wind speed; see Chapter 3.

Air-infiltration control not only conserves energy but also reduces ice buildup on the exterior of curtain wall components. Ice buildup is caused by the condensation of water vapor that escapes from the building's interior along with air. When the ice melts, the meltwater may leak into the building's interior. Therefore, a more stringent air-infiltration-control criterion is generally needed in colder climates.

RAINWATER- AND MELTWATER-PENETRATION CONTROL

Water-penetration control (of both rainwater and meltwater) is perhaps the most important nonstructural performance requirement of a glass curtain wall. Glass curtain wall systems are generally designed to ensure no water penetration when tested under a static air pressure difference (between the inside and the outside) that is at least 20% of the inward structural design wind load on the curtain wall. Thus, if the inward structural design wind load on the wall is 50 psf, the system is tested for water penetration under a static air pressure difference of at least 10 psf. A more stringent water-penetration criterion is required for buildings located in areas subjected to frequent and intense wind-driven rain. In addition to conforming to the static pressure criterion, a glass curtain wall is required to conform to dynamic pressure test criterion.

Water-penetration control is accomplished in different ways by system manufacturers; it typically includes adequate drainage in the aluminum joinery and glazing pockets. For example, in the stick-built glass curtain wall described earlier, weep holes are provided in the pressure plates and snap-on covers that drain the water to the outside. The architect's details must also ensure the management of water entering the curtain wall from a nonglass facade that is above the curtain wall, where such a facade exists.

NOTE

AAMA and Water Penetration

The American Architectural Manufacturers Association (AAMA) defines water penetration as the appearance of uncontrolled water other than condensation on the interior face of any part of the curtain wall.

U-VALUE, SOLAR HEAT GAIN, AND CONDENSATION RESISTANCE

These three interrelated criteria are a function of the type of glass, the type of aluminum framing (thermally improved or not), and the center-to-center spacing of framing members, as explained in Chapter 30. The architect must specify their values in consultation with the HVAC consultant (who also needs these values to design the building's HVAC system and to meet the energy code requirements).

VAPOR DIFFUSION ANALYSIS

As previously stated, interior water vapor may result in ice buildup on curtain wall framing and condensation of water vapor in the building's interior. These issues are particularly critical in cold climates, where a vapor analysis of the curtain wall system is generally required.

SOUND TRANSMISSION

Glass curtain walls in buildings located in areas where high levels of exterior noise are present (e.g., near airports or busy highways) may need a higher sound-transmission-loss specification than other areas.

HURRICANE IMPACT RESISTANCE AND SEISMIC RESISTANCE

Because of Florida's experience with extensive wind damage to glass curtain walls from hurricanes, several coastal cities in the United States are requiring that glass curtain walls be missile-impact resistant, particularly in the lower floors of the building. Similarly, because of California's experience with earthquake damage to glass curtain walls, resistance to shaking, glass drifting, and horizontal movement of components is required for buildings in seismically active areas.

THERMAL AND STRUCTURAL MOVEMENT

Aluminum-framing members and glass expand and contract due to temperature changes and the sudden cooling effects of precipitation. Glass curtain walls require sufficient expansion and contraction control built into them to allow thermal movement and the movement of spandrel beams due to live-load deflection. The expansion splice required in a stick-built curtain wall (Figure 32.3) accounts for this requirement.

GLASS-CLEANING-EQUIPMENT LOAD

High-rise curtain walls include provisions for periodic cleaning. This means that they must include anchorage points for the staging of cleaning equipment that is lowered from the roof to the front of the curtain wall. These anchors add point loads on the wall, and this information needs to be communicated by the architect to the system manufacturer.

32.7 OTHER GLASS-ALUMINUM WALL SYSTEMS

In addition to curtain walls, two additional glass-aluminum wall systems commonly used are

- Punched and strip glazing
- Storefront system

PUNCHED AND STRIP GLAZING

Punched glazing is similar to a punched window (see the window terminology in Chapter 31), except that the glass in punched glazing is generally fixed and site installed due to its large size. By contrast, a punched window is generally shop glazed and may contain operable sashes. The frame for punched glazing may be either shop assembled or stick-built on site. The frame is anchored to the opening (jambs, head, and sill) instead of being anchored to the building's structural frame (as in a curtain wall).

Strip (also called *ribbon*) glazing is similar to punched glazing, with several glazing units placed in a linear alignment. Strip glazing is also anchored to the head and sill of an opening.

STOREFRONT SYSTEM

A storefront is a large glass-aluminum wall that is generally one-story tall and extends from the ground to the second floor of the building. Three major differences distinguish a curtain wall from a storefront. They are as follows:

(a) The storefront wall lies under the second-floor structure of the building and (unlike a curtain wall), it is not spaced away from the structural frame of the building. Often, a storefront is protected by an overhang to control water leakage through the system.
(b) The glazing system's performance for structural and nonstructural criteria (air infiltration, water penetration, CRF, etc.) is lower than that of a curtain wall.
(c) Rainwater that enters a curtain wall is drained by the (horizontal) rail support of each individual lite. In a storefront system, the water entering through a lite must travel vertically down the mullion and be drained at the weep holes at the ground level.

32.8 NONTRADITIONAL GLASS WALLS

The glass-aluminum wall types discussed so far are traditional types that have evolved over a long period. Three recently introduced systems that do not rely on aluminum sections for support are

- Glass wall supported by cable trusses
- Glass wall supported by a pretensioned cable net
- Double-skin glass walls

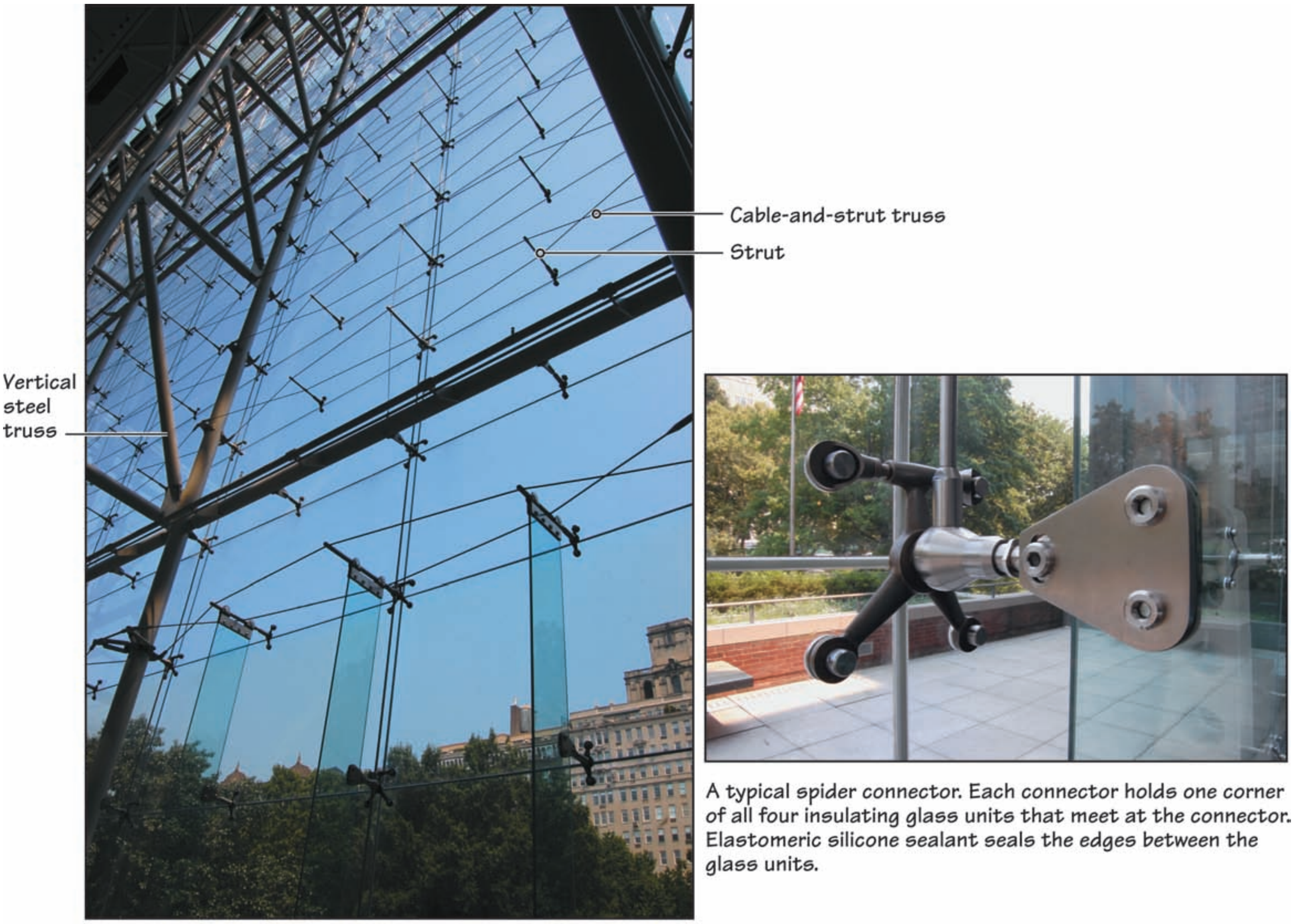
GLASS WALL SUPPORTED BY CABLE TRUSSES

A sophisticated and unique version of a glass wall that is relatively uncommon (due to its cost) is the mullionless glass wall developed by the Pilkington Company. In this system, each glass pane is suspended at four corners by stainless steel *spider-shaped connectors*. The connectors are held by a horizontal truss consisting of stainless steel tension cables and compression struts. Several such trusses are anchored to vertical steel frames, Figure 32.17.

The glass used in the system is generally a high-R-value, insulating glass unit with laminated and heat-soaked tempered glass (see Section 30.2). Only elastomeric, silicone sealant separates a glass pane from the adjacent panes.

GLASS WALL SUPPORTED BY A PRETENSIONED CABLE NET

Another recently introduced glass wall system is one that uses a grid of pretensioned (stretched) cables to support the glass. Conceptually, the support system resembles a



A typical spider connector. Each connector holds one corner of all four insulating glass units that meet at the connector. Elastomeric silicone sealant seals the edges between the glass units.

This glass wall is supported by a two-directional (consisting of horizontal and vertical elements) backup structure. The horizontal elements of the backup structure consist of trusses with tension cables and compression struts. The vertical elements consist of trusses made of steel pipes. The glass is held by spider connectors, which are connected to the compression struts. At a level close to the floor where tension cables and compression struts cannot be used, glass fins have been used to provide lateral support to the glass.

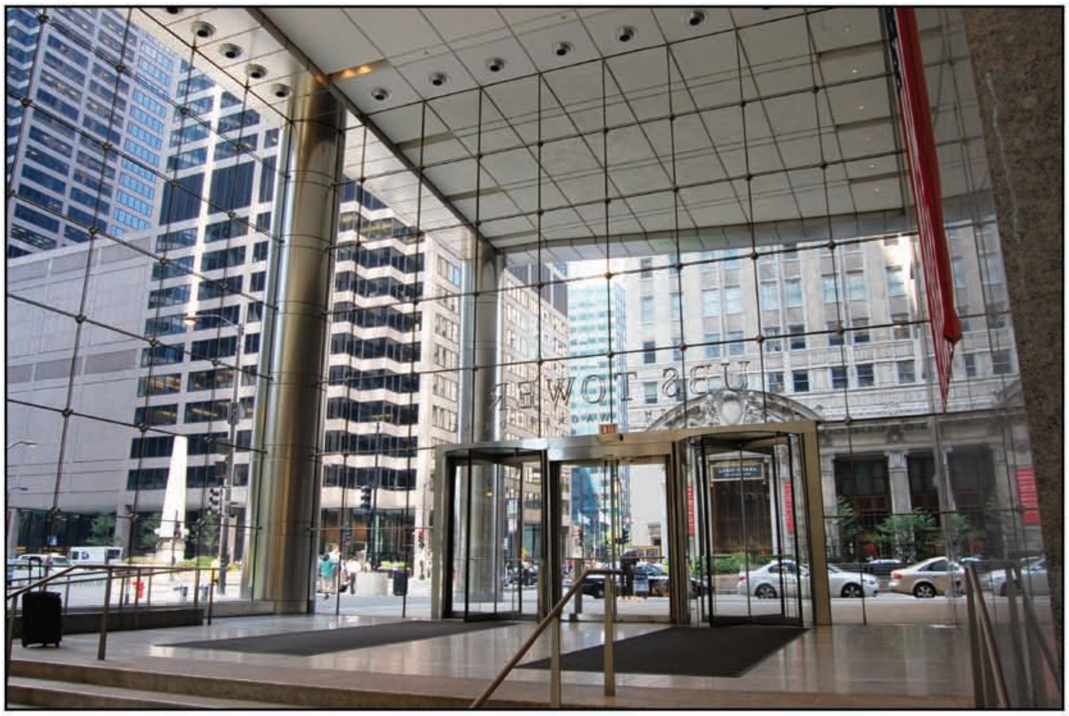
FIGURE 32.17 Pilkington's Planar Glass Wall System used in the Rose Center for Earth and Space, New York City (see also Chapter 30, Figure 30.4). Architects: Polshek Partnership.

two-directional grid of strings in a tennis racket. Because the strings in a tennis racket are highly stretched, they create a stiff plane. When held vertically, the stringed plane of the racket resembles a stiff wall that can resist lateral loads and can be used to suspend planar elements from it.

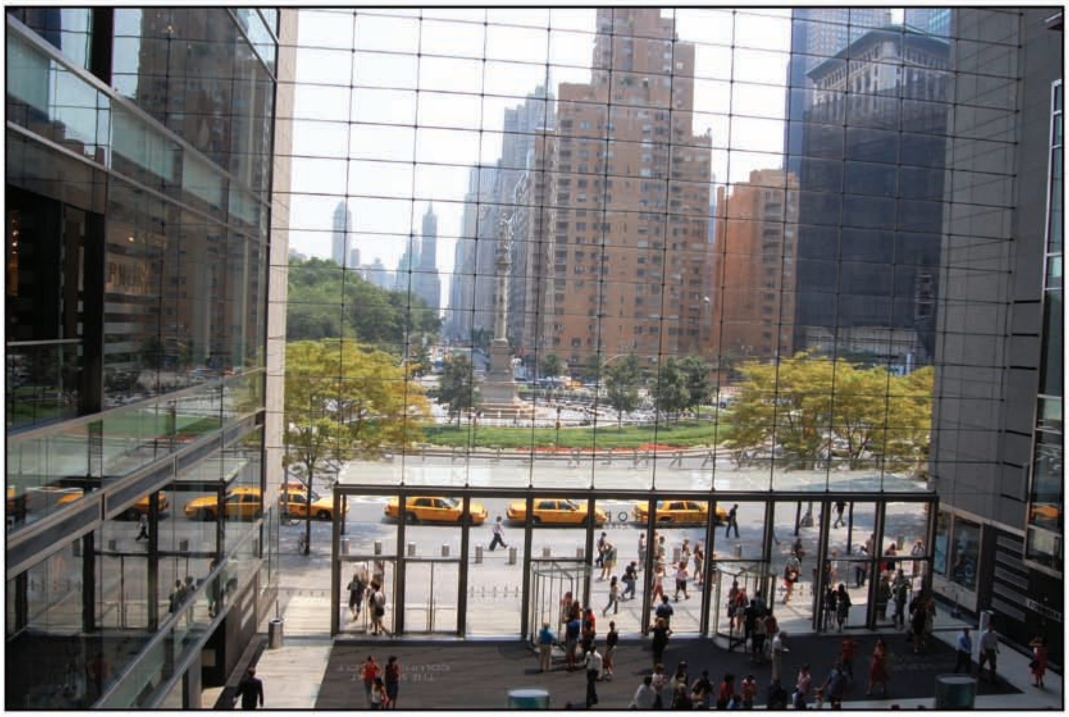
Similar to the stringed plane of a tennis racket, a cable-net-supported glass wall consists of pretensioned (approximately 1-in.-diameter) stainless steel cables arrayed in both the horizontal and vertical directions. The vertical cables are stretched between the top and bottom of an opening—generally between the spandrel beams at the upper and lower floors. The horizontal cables are stretched between the sides of the opening—generally between the columns or walls supporting the building. Two examples of cable-net-supported glass walls are shown in Figures 32.18(a) and (b).

The horizontal and vertical cables are held together at intersections through special stainless steel connectors, which also serve as points for securing the glass to the grid. A typical connector is shown in Figure 32.18(c). The glass panels generally consist of insulating glass units with laminated and heat-soaked tempered glass.

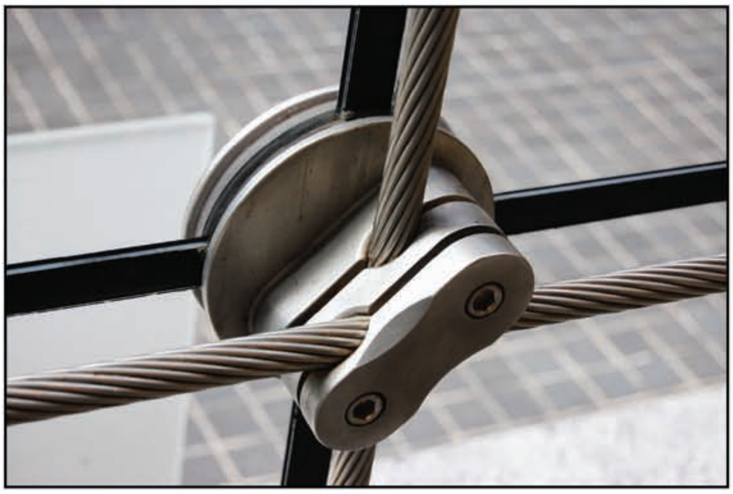
Because the cables are highly stressed, they impose a large load on the boundary elements of the opening—the two spandrel beams and the columns (or walls)—which must be designed to resist this additional load.



Cable-net glass wall in the entrance lobby of One North Wacker Building, Chicago, Architects: Goettsch Partners.



Cable-net glass wall in the atrium of Time Warner Center, New York City. Architects: Skidmore, Owings, and Merril.



Typical connector at a node—the point of intersection between cables. The connector connects the cables together and also provides support to the glass. Four glass corners meet at each connector.

FIGURE 32.18 Two examples of cable-net-supported glass walls. Note that all photographs have been taken from inside the buildings.

DOUBLE-SKIN GLASS WALLS

Another innovative glass wall system is the double-skin wall system, also referred to as a *bio-climatic glass wall*. In this system, two glass walls, separated by 1 ft to 5 ft of air space, are used. The air space serves as a buffer between the two skins, tempering the outdoor air, and also serves as a plenum for the building's HVAC system. The outer skin may include computer-controlled operable glazing and solar shading devices.

Although the primary benefit of a double-skin system is energy conservation, it also provides effective water-penetration control, better air-infiltration control, higher sound insulation, and so on. The proponents of the system, which has been used extensively in Europe, claim it to be more sustainable under the present energy prices in Europe, which are considerably higher than those in the United States.

As smart glazing systems with environment-adaptive technologies (e.g., electrochromic glass) and energy-generating capabilities (e.g., photovoltaic glass) evolve further, double-skin glass wall systems may become more popular. In that scenario, the outer glass skin may not only help conserve energy but also generate some energy to power the building.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

20. The air infiltration rate through a glass curtain wall is specified in terms of
- **a.** pounds per square feet.
- **b.** cubic feet per minute.
- **c.** cubic feet under a given inside-outside air pressure difference.
- **d.** cubic feet per minute under a given inside-outside air pressure difference.
- **e.** none of the above.

21. In a glass wall supported by cable trusses, the glass
- **a.** bears on (horizontal) rails.
- **b.** is connected to (vertical) mullions.
- **c.** (a) and (b).
- **d.** none of the above.

22. In a cable-net-supported glass wall, the glass
- **a.** bears on (horizontal) rails.
- **b.** is connected to (vertical) mullions.
- **c.** both (a) and (b) above.
- **d.** is supported by a spider-shaped connector.
- **e.** none of the above.

23. The environmental performance requirements for a storefront are generally much higher than those for a glass curtain wall.
- **a.** True
- **b.** False

REVIEW QUESTIONS

1. Using sketches and notes, explain the differences between a single-span mullion support system and a twin-span mullion support system for a glass curtain wall.
2. Use three-dimensional sketches to illustrate each of the following:
   a. A typical dead-load anchor used in a glass curtain wall
   b. A typical expansion anchor used in a glass curtain wall
3. Sketch in three dimensions a typical spider-shaped connector.
4. List the major differences between a glass curtain wall and a storefront.
5. Explain the purpose of the following items and state where they are used: (a) shear block, (b) pressure plate, and (c) adapter for spandrel glass.
6. Using sketches and notes, explain how we increase the lateral load–bearing capacity of a standard glass-aluminum wall.

CHAPTER 33

Roofing-I
(Low-Slope Roofs)

CHAPTER OUTLINE

33.1 Low-Slope and Steep Roofs Distinguished
33.2 Low-Slope Roof Fundamentals
33.3 Built-Up Roof Membrane
33.4 Modified Bitumen Roof Membrane
33.5 Single-Ply Roof Membrane
33.6 Attachment of Low-Slope Roof Components
33.7 Insulating Concrete and Membrane Attachment
33.8 Low-Slope Roof Flashings
33.9 Base Flashing Details
33.10 Curb and Flange Flashing Details
33.11 Protected Membrane Roof
33.12 Low-Slope-Roof Design Considerations
PRINCIPLES IN PRACTICE: Shingling of Built-Up Roof Felts

The roof is one of the most critical components of a building. It is one of the primary sources of construction litigation and building owners' complaints. One estimate indicates that nearly 65% of all lawsuits brought against architects originate in roofing problems [Ref. 33.1]. This statistic becomes significant considering that the roof covering of a typical building is replaced every few years—12 to 14 years on the average. Would we accept replacement of other components of a building envelope—doors, windows, curtain walls, and so on—so frequently? A major reason for this situation is the severity of physical and chemical degradation, by solar radiation, rainwater, snow, hail, and windstorm, to which a roof is subjected. Another reason is the ever-increasing complexity of contemporary buildings and, more specifically, of contemporary roofs.

Until the mid-twentieth century, roofing alternatives were few and roof design was relatively simple. For a flat roof, the roofing membrane consisted of either a coal tar or an asphalt built-up roof on a concrete or wood deck. For a steep roof, clay tiles or wood shingles were the major alternatives. This is not true today. The relatively sudden spurt in the gross national products of Western economies after World War II introduced large industrial buildings with relatively light steel roof decks. A roof that performed well on a stiff concrete or wood deck failed prematurely on a light, flexible steel deck.

The advent of air conditioning and more efficient heating systems led to urban development in extremely warm and cold climates. Roof insulation that was seldom used earlier became the norm. The greater degradation of roofs in extremely hot and cold climates, and the effect of roof insulation, introduced factors whose impact was not realized until several years later.

The oil embargo of 1973 led to significant increases in the cost of asphalt-based built-up roofs, which made single-ply roofs economically competitive for the first time. This, combined with several other market forces, resulted in a significant increase in the market share of single-ply roofs. Some of the early single-ply roofs had a fairly brief history of use, which further increased roofing problems. Although roofing products are generally subjected to several laboratory tests before being introduced in the market, none of these tests can fully simulate the actual field conditions.

This chapter is the first of two chapters on roofing. It begins with a general introduction to roofing, including the basis for distinguishing between low-slope and steep roofs. Subsequently, various aspects of low-slope roofs are covered. Steep roofs are discussed in the following chapter.

33.1 LOW-SLOPE AND STEEP ROOFS DISTINGUISHED

A discussion of roofing must begin with its classification into two types:

- Low-slope roof
- Steep roof

A low-slope roof is a *water-resisting* roof and consists of a continuous roof membrane over a relatively flat roof surface. Although water ponding is generally to be avoided, a low-slope roof has to be designed for a certain depth of rainwater accumulation that might occur in the event of blockage of the roof's drainage system. The depth of rainwater accumulation is predetermined based on the roof's geometry and the design of its drainage system. The roof membrane in a low-slope roof must, therefore, act as a waterproofing membrane and be able to resist the rainwater load and water leakage until the drainage system is able to function again. This period may range from a few hours to a few days.

A steep roof, also called a *water-shedding* roof, typically consists of small individual roofing units (shingles) that overlap each other. The roof surface must be sloped so that the water is shed off the roof by gravity. The slope must generate adequate gravitational force to overcome the forces produced by wind, head pressure, and capillary action that might push the water up the slope between adjacent shingles and cause the roof to leak. Double coverage in shingles and adequate overlap are necessary to prevent roof leakage.

The rate of discharge of water from the roof is not only critical in keeping the roof and the building's interior dry, it is also one of the most important factors in establishing the durability of the roof. There are sufficient long-term data to confirm that—everything else being the same—the durability of a roof increases directly with the slope of the roof. Steep roofs, in general, outsurvive low-slope roofs.

A low-slope roof is defined as a roof with a slope of less than 3:12 (25% slope) and greater than $\frac{1}{4}$:12 (2% slope). A dead-flat roof is not permitted by the building codes. A steep roof is defined as a roof with a slope greater than or equal to 3:12.

Despite the greater durability of a steep roof, the market share of low-slope roofs is nearly twice as large as that of steep roofs, Figure 33.1 [Ref. 33.2]. Low-slope roofs are generally used for commercial and industrial buildings and are mostly constructed to a minimum

NOTE

Low-Slope Roof and Steep Roof

Low-slope roof slope $< 3:12$
Steep roof slope $\geq 3:12$

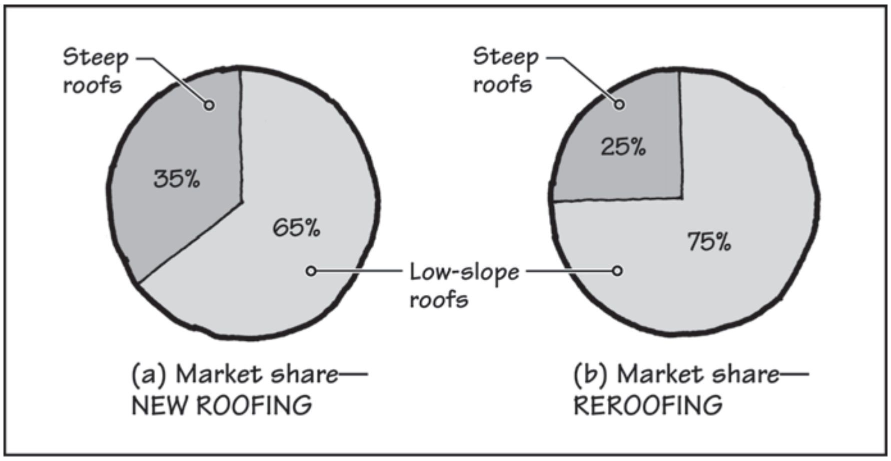


FIGURE 33.1 Approximate market shares of low-slope and steep roofs.

mandated slope of $\frac{1}{4}$:12. This slope, which yields an almost flat roof, makes the structural framing of the roof and the supporting structure most economical because an increase in roof slope increases the roof area, the dimensions of framing members, and the related structure. Additionally, a flat roof provides an easily accessible space for installing HVAC and other equipment. Buildings with flat roofs generally have their HVAC equipment mounted on the roofs. Steep roofs, which are generally used for low-rise residential buildings (single-family homes, apartment buildings, motels, etc.), have their HVAC equipment placed on the ground.

A low-slope roof also makes maintenance and reroofing, particularly on high-rise buildings, relatively easy. Imagine reroofing or repairing a steep roof a few hundred feet above the ground!

33.2 LOW-SLOPE ROOF FUNDAMENTALS

A low-slope roof has the following four major components, Figure 33.2:

- Roof membrane, including a protective cover above the membrane, where needed
- Cover board
- Insulation
- Roof deck
- Flashings

In some roofs, particularly in cold regions or over high-humidity enclosures, a vapor retarder may also be needed.

ROOF MEMBRANES

The roof membrane is the most important component of a roof because it is the waterproofing layer. Being the top layer, it is constantly subjected to the weathering effects of Sun, rain, snow, hail, and wind. Roof membranes are divided into three general categories:

- Built-up roof membrane
- Modified bitumen roof membrane
- Single-ply roof membrane

A *built-up roof membrane* consists of three to five plies (layers) of felt with intervening moppings of bitumen (asphalt or coal tar). Because both asphalt and coal tar are adversely affected by ultraviolet radiation, a built-up roof membrane is generally protected by an aggregate cover. The aggregate cover also increases the roof's fire resistance. Of the two, asphalt built-up membranes are far more common than coal tar built-up membranes.

A *modified bitumen roof membrane* is similar to a built-up roof membrane and comprises two to three plies of modified bitumen sheets with intervening moppings of bitumen. A protective aggregate cover or a mineral granule—surfaced cap sheet is required.

A *single-ply roof membrane* consists of only one sheet of a synthetic polymer (plastic) and does not require any protective cover. Although slightly variable, the relative market shares of built-up, modified bitumen, and single-ply roof membranes are approximately the same—nearly one-third each.

ROOF COVER BOARD

A cover board is installed between the membrane and the insulation. As a transition element, it must obviously be compatible with both membrane and insulation. It must also be

NOTE

Metal Panel Roofs and Protected Membrane Roofs

In a typical membrane-covered low-slope roof assembly, the membrane deteriorates more rapidly due to its exposure to weathering elements. In response to this weakness, two other low-slope roofs have gradually increased their market shares:

- Metal panel roofs
- Protected membrane roofs

A metal panel roof consists of thin sheets of metal bent into panels that are laid over roof insulation and anchored to the deck. They may be used in low-slope or steep roofs, although they function better on steep slopes (slope greater than 3:12). The initial cost of metal panel roofs (a nonmembrane roof assembly) is higher than that of membrane roofs. Metal panel roofs are discussed in Chapter 34.

In a protected membrane roof, the insulation is loose laid over the deck to which the membrane is attached directly. The protected membrane roof is discussed later in this chapter.

Fluid-Applied Membrane Roofs

Fluid-applied membrane roofs consist of polyurethane foam insulation sprayed over a low-slope roof deck. The insulation is covered with a (fluid) coating that cures into a membrane. It is commonly used in the southern and southwestern United States and has a relatively small overall market share.

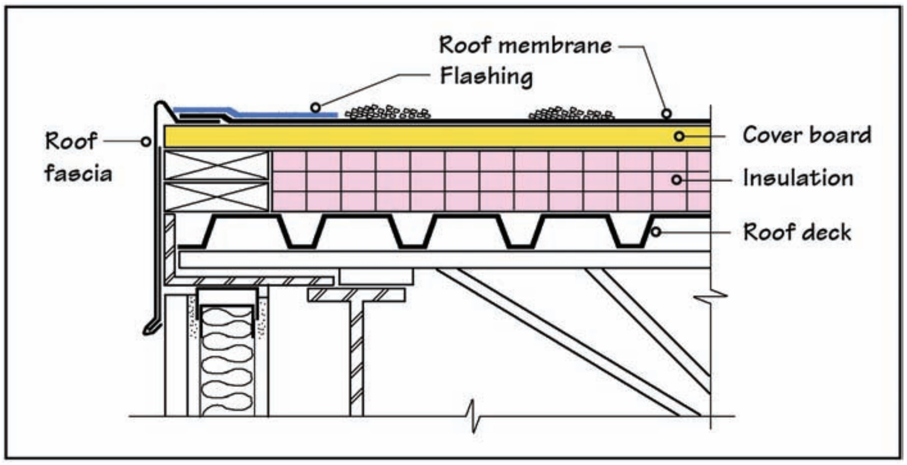


FIGURE 33.2 Four major components of a low-slope roof—roof deck, insulation, cover board, roof membrane, and flashings. Although this sketch shows an edge guard roof fascia, low-slope roofs are also provided with a parapet.

compatible with any adhesive used between the cover board and the membrane, and between the cover board and insulation.

The cover board commonly used for hot-mopped roofs (built-up and modified bitumen roofs) is perlite board or fiberboard, typically $\frac{3}{4}$ in. to 1 in. thick. For single-ply roofs, the cover board used is glass fiber–reinforced gypsum board, typically $\frac{1}{4}$ in. to $\frac{5}{8}$ in. thick. Gypsum board is unsuitable with hot-mopped membranes because of the amount of water present in it, which converts to steam due to the high temperature of asphalt. Perlite board and fiberboard, on the other hand, can withstand asphalt's high temperature (400–450°F). (See Section 16.8 for the amount of chemically combined water present in gypsum board.)

The general lack of compatibility between the adhesives used for adhering the membrane to the insulation is the primary reason for the use of a transition element—the cover board. For example, mopping the built-up or modified bitumen membranes with hot asphalt directly on the insulation creates blistering problems. The use of a cover board (perlite board) eliminates these problems. Gypsum cover board does the same with fully mopped single-ply membranes.

An additional advantage of using cover boards is their greater dimensional stability to temperature extremes than roof insulations. The reader will note from Section 9.4 that the plastics have much greater thermal expansion coefficients than other materials. Because low-slope roof insulations are rigid board plastic foams, they bow upward in hot weather due to expansion. In cold weather, gaps are created between boards due to contraction, leaving the roof membrane without support. The use of cover board alleviates this problem.

Perlite board, fiberboard, and gypsum board are far more rigid than the typical roof insulations. Therefore, a cover board adds to the rigidity of components under the membrane, which provides the following benefits.

- It increases the roof's durability against foot traffic by reducing membrane punctures.
- It increases the roof's resistance to hail impact.
- It increases the roof's wind-uplift resistance.
- It provides a more robust surface for solar array installation.
- It provides a thermal break due to staggered (offset) joints between cover board and insulation, particularly if only a single-layer insulation is used.

ROOF INSULATION

The insulation is an essential component of a roof because it reduces energy consumption. Because a low-slope roof is subjected to foot traffic, the insulation used must have sufficient rigidity. On steel roof decks, which are fluted, rigidity of insulation provides surface flatness.

Rigid board plastic foam insulations—extruded polystyrene (XPS) or polyisocyanurate (polyiso)—is commonly used in low-slope roofs. Of the two, polyiso is far more common because of its greater R-value and greater resistance to high temperature. (The R-value of 1-in.-thick polyiso = 6.5; the corresponding R-value of XPS = 5.0, see Table 5.2.)

ROOF DECK

A low-slope roof deck may be of steel, wood, cast-in-place concrete, precast concrete, gypsum concrete, or wood fiber—cement deck. Steel and concrete roof decks are more commonly used in low-slope roofs.

ROOF FLASHINGS

Flashings are an integral part of a low-slope roof. They are required at roof terminations, such as the free edges of a roof, at parapets, and at roof expansion joints. Flashings are also required at penetrations, such as around interior roof drains, and around pipe or tubular supports for rooftop equipment, see Section 33.8.

LOW-SLOPE ROOF—A SYSTEM OF COMPATIBLE COMPONENTS

Each roof component must obviously serve its own function, but it must also be compatible with other roof components. For instance, the insulation must not only give the required R-value, but also provide a rigid substrate against hail and foot traffic. It should also have long-term chemical compatibility with the deck and the cover board.

Similarly, the roof deck must not only provide the required structural support for the entire assembly and other loads, but also be dimensionally stable to prevent the over-stressing of the insulation and the membrane. It must provide a suitable base for the anchorage of insulation and the membrane and have adequate fire resistance.

With several factors that affect its performance, and with several components and subcomponents that constitute a low-slope roof, roof design must be considered a system design. It should consider the interaction between roof components and the effects of external factors such as the external climate, solar radiation, wind, rain, hailstorms, fire, and rooftop traffic (necessitated by the equipment's and roof's maintenance operations). The selection of all components of the system, including fasteners and adhesives, from the same manufacturer is, therefore, important in the case of a low-slope roof. Where a manufacturer does not make all components of the system, components approved by the primary manufacturer must be used to ensure their compatibility.

33.3 BUILT-UP ROOF MEMBRANE

A typical built-up roof membrane consists of a felt laid over a mopping of bitumen, followed by a second mopping of bitumen, then by the second felt, and so on. In other words, a number of felt layers (called plies), separated by interply moppings of bitumen, constitute a built-up roof membrane.

The greater the number of plies, the thicker and, hence, stronger and more durable the membrane. Three to five plies is generally the norm. The last ply is typically covered with a surfacing material to protect the entire membrane from the effects of weather and external fire. The most common surfacing material is stone aggregate laid over a flood coat of bitumen. Because the quantity of bitumen for the flood coat is much greater than that required for interply moppings, it is poured over the roof, whereas the interply bitumen is simply mopped on. Figures 33.3(a) to (f) illustrate a few stages in the laying of a typical built-up roof membrane.

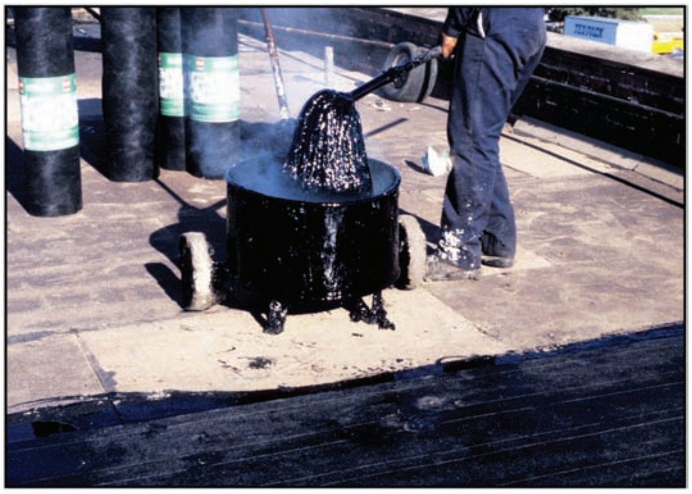


FIGURE 33.3(a) With a bucket full of hot bitumen and a mop, a roofer begins to lay a built-up roof.

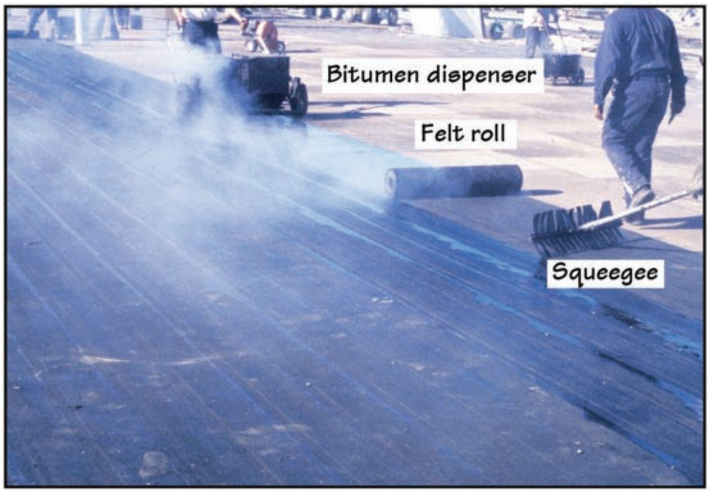


FIGURE 33.3(b) Immediately after laying a coat of hot bitumen as shown in Figure 33.3(a), a built-up roof felt is unrolled over it. Although the bitumen can be applied with mops, it is more convenient to use bitumen dispenser on large roofs. The unrolling of felt over bitumen is followed by pressing the felt down with a squeegee.

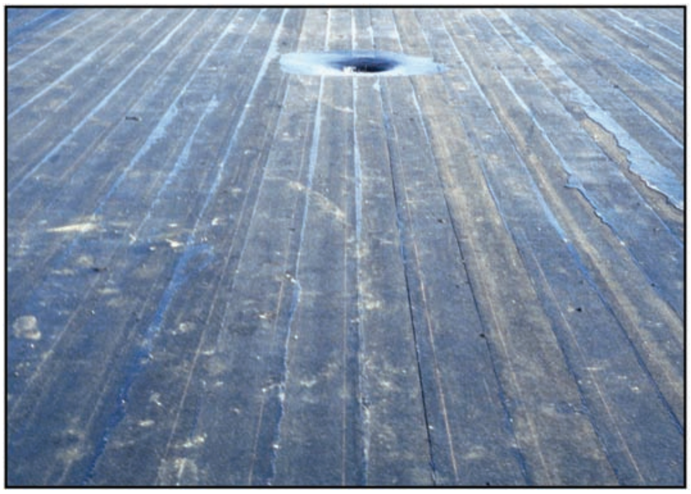


FIGURE 33.3(c) This image shows the roof after all built-up felt plies have been applied. The roof is now ready to receive the flood coat of bitumen and stone aggregate surfacing, as shown in the following two images.

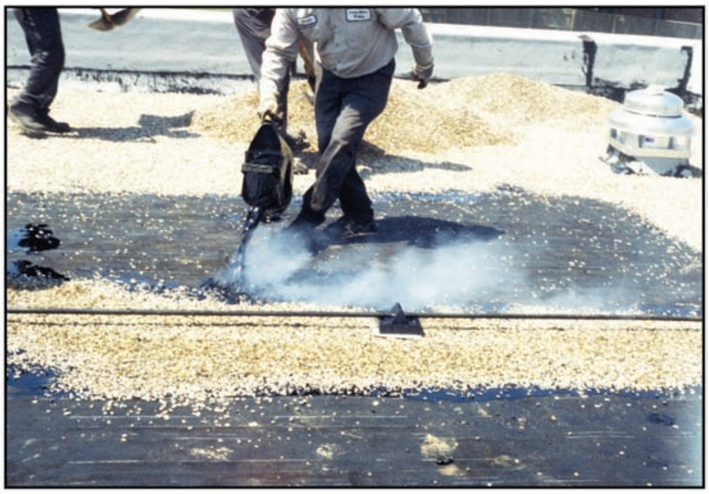


FIGURE 33.3(d) The bitumen under aggregate surfacing is poured over the deck, not mopped. That is why it is called a "flood coat" of bitumen.

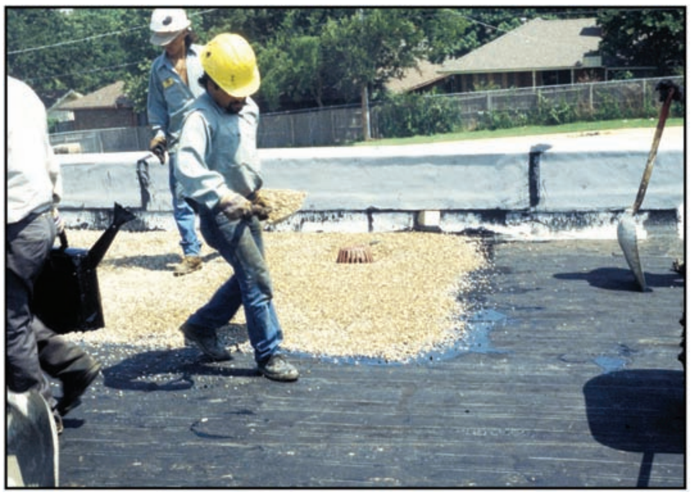


FIGURE 33.3(e) Bitumen flood coat is covered with stone aggregate. For a small roof, shovels are used to spread the aggregate.

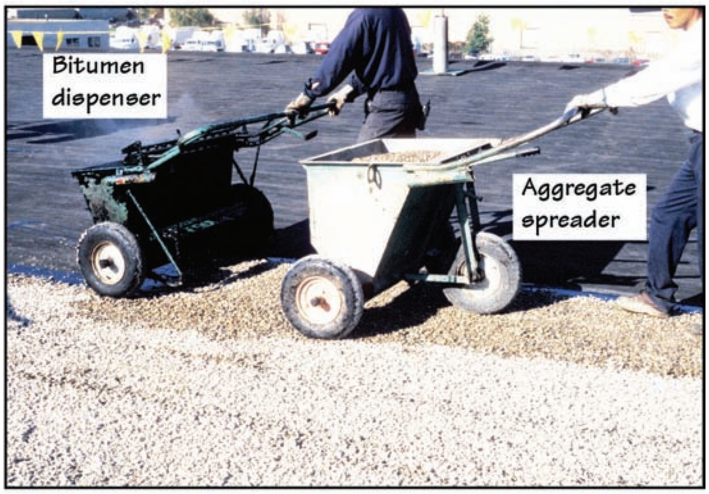


FIGURE 33.3(f) Although the bitumen for a flood coat can be poured with buckets, as shown in Figure 33.3(d), it is usually poured on large roofs using a bitumen dispenser followed by aggregate spreader.

In the alternate layers of felt and bitumen in a built-up roof, the bitumen is the waterproofing material. However, bitumen alone cannot be used, because it is a thermoplastic material. It becomes soft at high temperatures and begins to flow. At low temperatures, it becomes hard and brittle and cracks. Thus, bitumen does not have the requisite tensile strength to withstand the stresses imposed by the changes in temperature, deck movement, foot traffic, hailstorms, and so on.

The felts work as reinforcing material, giving the required tensile strength to the membrane, Figure 33.4. The felts also stabilize the bitumen against flow, because the interwoven felt fibers form mini-receptacles within which the bitumen is held, preventing its flow, Figure 33.5. A heavy mopping of bitumen without felt simply cracks in cold weather, due to the lack of tensile strength, and flows like a thick paste during hot weather, due to the lack of containment. Thus, the felts allow for a more significant buildup of bitumen, which increases the weatherproofing and waterproofing of the membrane.

ORGANIC AND FIBERGLASS ROOF FELT

A built-up roof felt consists of fibers (or strands) pressed into a sheet. A felt may be either an *organic felt* or an *inorganic felt*, depending on whether the fibers are organic or inorganic. Organic felt is made from paper or wood fibers or a combination of both. Inorganic felt is made from glass fibers.

The manufacturing process for both organic and fiberglass felts is similar to that of paper making in that a mass of fibers is pressed under rollers to give a thin, flat sheet. In fact, untreated organic felt (without the bitumen treatment) is virtually indistinguishable from thick handmade paper.

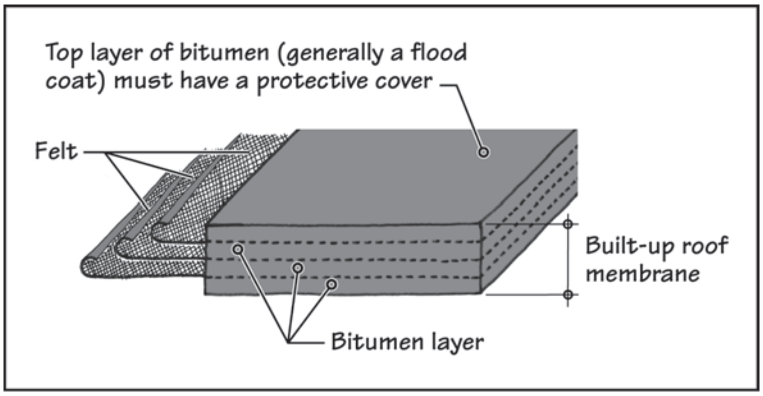

Top layer of bitumen (generally a flood coat) must have a protective cover
Felt
Built-up roof membrane
Bitumen layer

FIGURE 33.4 A built-up roof membrane consists of alternate layers of bitumen moppings and felts. The felts provide tensile strength to the membrane, in which the bitumen is the waterproofing agent. The greater the number of felts, the stronger the roof membrane.

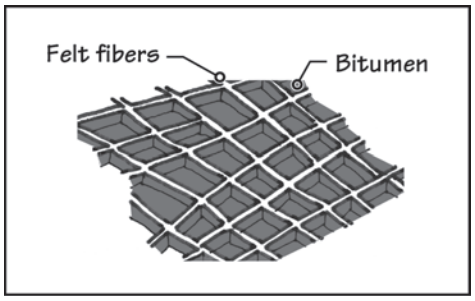


FIGURE 33.5 Interwoven felt fibers form miniature containers to hold the bitumen, preventing its flow.

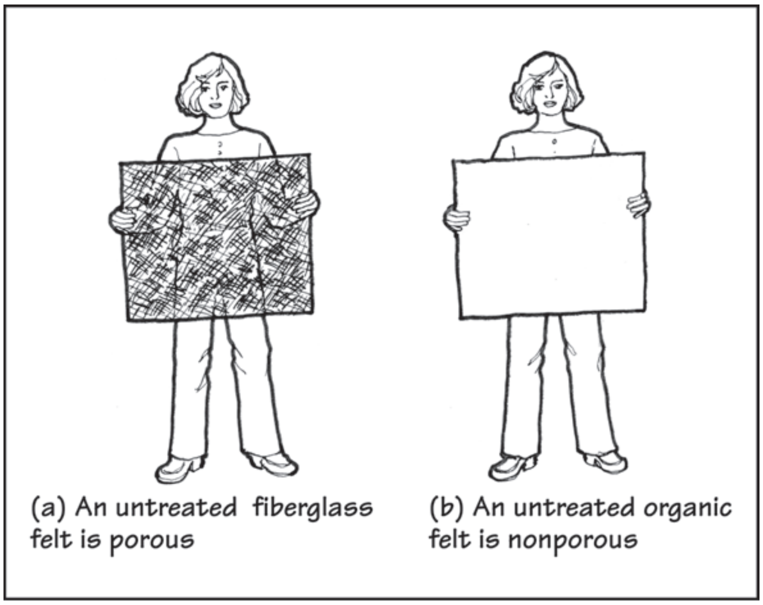

(a) An untreated fiberglass felt is porous
(b) An untreated organic felt is nonporous

FIGURE 33.6 The partial visibility of the person holding an untreated fiberglass felt indicates its sparse weave. By comparison, an organic felt is opaque and nonporous.

Untreated fiberglass felt, on the other hand, looks like a woven mat. The weave in fiberglass felt is so sparse that light and air can easily pass through it. By comparison, organic felt is thick, nonporous, and opaque to light, Figure 33.6.

After the rolling process, felt is treated with bitumen. Because both coal tar and asphalt are black in color, treated felt is black. Treated felt is used in a built-up roof. Therefore, the term *felt* in our discussion generally implies a bitumen-treated felt. The treatment consists of simply covering the felt with bitumen.

Although treatment with bitumen reduces the porosity of fiberglass felt, treated fiberglass felt is still highly porous. Treated organic felt is nonporous and, hence, water resistant, Figure 33.7. Generally, organic felt is specified as an underlayment for roof shingles and tiles. Because of its porosity, fiberglass felt cannot be used in such applications (see Chapter 34).

The porosity of fiberglass felt is, however, an advantage in built-up roof applications. Because the asphalt at the time of application is at a high temperature (nearly 400°F), any air trapped during mopping expands and forms blisters under the felt if it is not allowed to escape. If there is any moisture in the substrate, it turns into steam and also forms blisters if

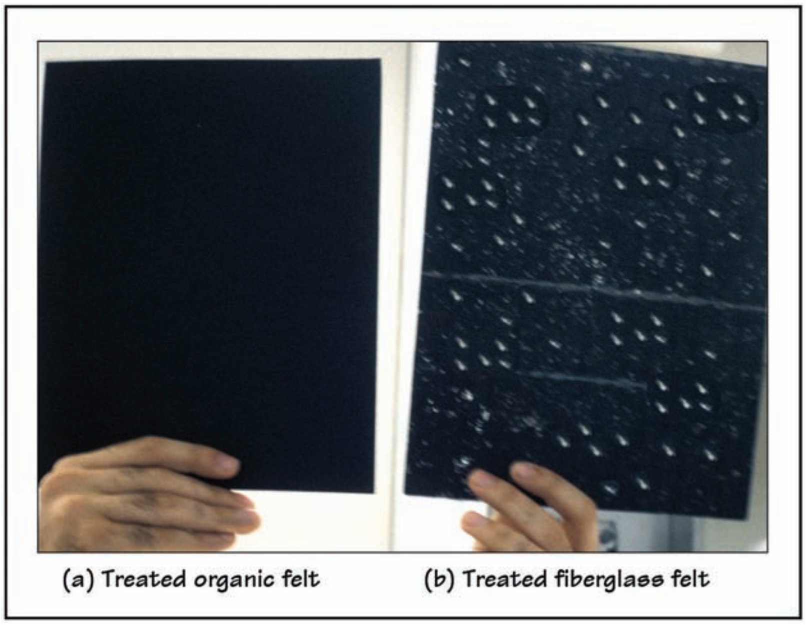


FIGURE 33.7 Although less so than an untreated fiberglass felt, a treated fiberglass felt is fairly porous. A treated organic felt is nonporous and, hence, useful as a water-resistant underlayment in steep roofs, see Chapter 34.

it is unable to escape. Blisters obviously weaken the roof membrane, because they represent areas where the roof is unattached to the substrate. The pressure exerted on the membrane by the water vapor and air inside the blister can exceed the tensile strength of the membrane, causing its rupture. The inherent porosity of fiberglass felt allows trapped air and vapor to escape. Therefore, fiberglass felt is commonly used in built-up roofs.

Felt is typically manufactured in 36-in.-wide rolls, although metric (1-m-wide) felt is also available from a few manufacturers. Because bitumen is a highly tacky substance, the felt is surfaced with fine mineral sand or another release agent to prevent its adhesion inside the roll.

JM
Johns Manville
GlasPly® Premier
Premium Fiber Glass Ply Felt
5 Square (48.45 Square Meters)
One Square Covers 100 Sq. Ft. (9.29 Sq. Meters) of Roof
Meets ASTM D 2178, Type VI (6)
Roofing Systems Group
717 17th Street, Denver, CO 80202, www.jm.com
800 654 3103 303 978 2318 FAX

A Type VI felt roll.

TYPES OF FIBERGLASS FELT

There are two types of fiberglass felt:

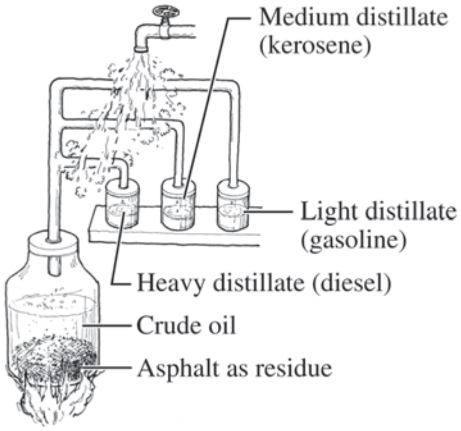
Asphalt-treated fiberglass felt: Asphalt-treated fiberglass felt is classified as either Type IV or Type VI, having a tensile (or tear) strength of 44 lb/in. and 60 lb/in., respectively. Type VI, the stronger felt, is recommended where the membrane is subjected to high tensile stresses. These stresses may be caused by a high daily or annual temperature differential, a relatively flexible deck, or excessive impact on a roof due to hailstorms and/or foot traffic. In addition to using Type VI felt, a thicker (four- to five-ply) built-up roof membrane is recommended for the preceding situations, since a thicker membrane is stronger.

Coal tar–treated fiberglass felt: The use of tar-treated fiberglass felt has been decreasing. Coal tar fumes can produce extreme discomfort for the installers. Additionally, due to the porosity of fiberglass felt and the cold-flow property of tar, the tar filters through the felt, so that the felt tends to sink to the bottom of the membrane. This separates the felt from the bitumen.

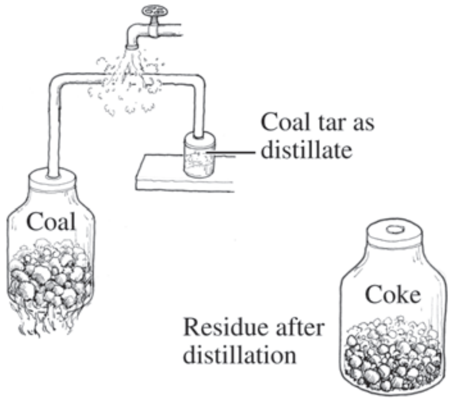
BITUMEN—ASPHALT AND COAL TAR

Two types of bitumen—*asphalt* and *coal tar*—are used in built-up roofing. Asphalt is the waste product (residue) obtained from the distillation of crude oil at petroleum refineries. Coal tar (also called *tar* or *pitch*) is obtained from the distillation of coal. Although the distillate in this process is coal tar, the residue is coke. Coke is used in the steel manufacturing industry (see Section 18.1).

Although both asphalt and coal tar are highly resistant to water, coal tar is slightly more so. Coal tar built-up roof manufacturers claim that their roofs withstand ponded water, a claim not advanced by asphaltic built-up roof membrane manufacturers. However, asphalt built-up roofs are far more commonly specified than coal tar built-up roofs, although asphalt appeared on the scene much later. The primary reason is the significantly lower health risk to roofers from the use of asphalt compared to coal tar. The other benefits of asphalt are its greater availability and lower cost compared to coal tar.


Medium distillate (kerosene)
Light distillate (gasoline)
Heavy distillate (diesel)
Crude oil
Asphalt as residue

Distillation of crude oil.


Coal tar as distillate
Coal
Coke
Residue after distillation

Distillation of coal.

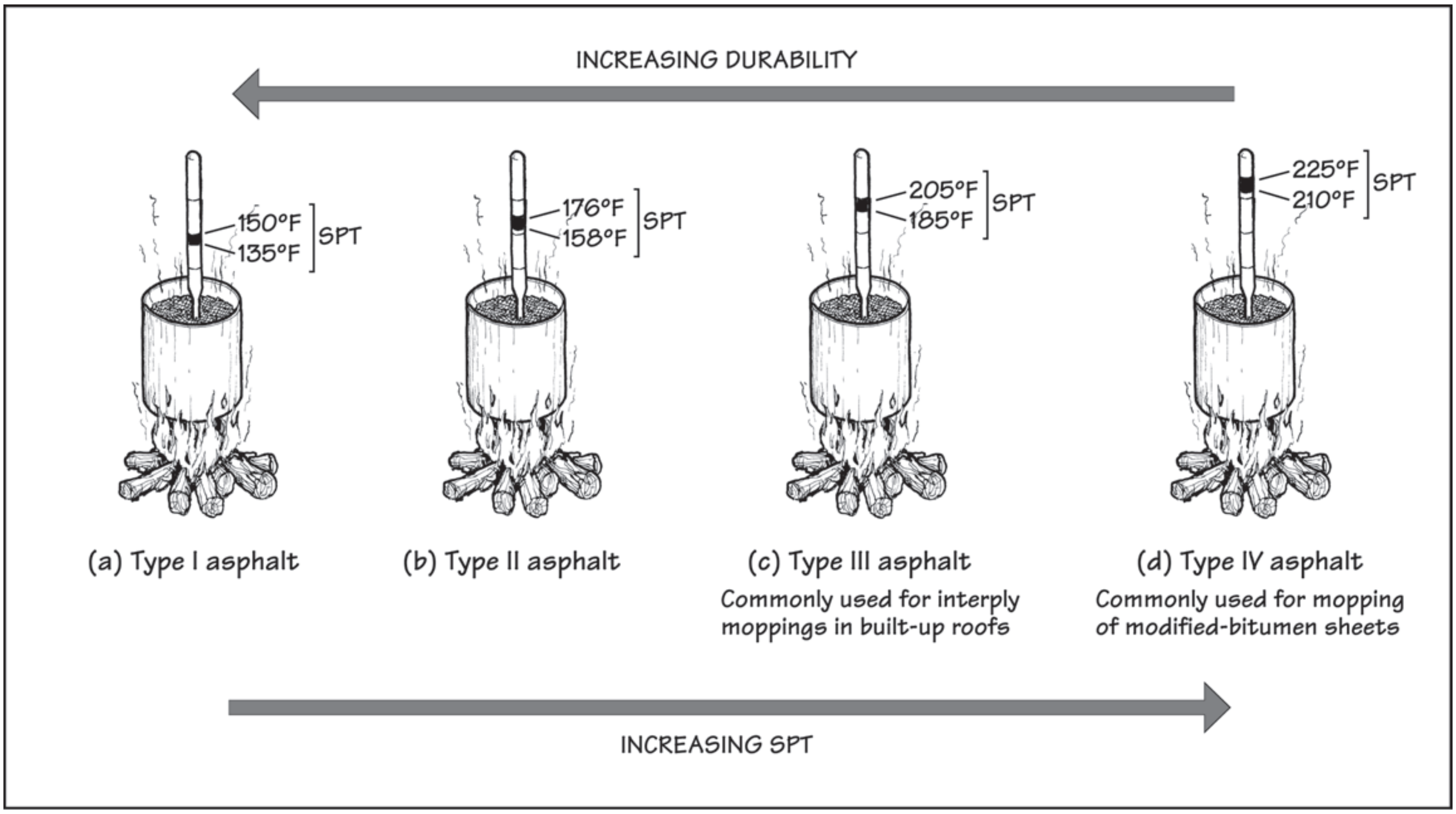

INCREASING DURABILITY
150°F
135°F
SPT
176°F
158°F
SPT
205°F
185°F
SPT
225°F
210°F
SPT
(a) Type I asphalt
(b) Type II asphalt
(c) Type III asphalt
Commonly used for interply moppings in built-up roofs
(d) Type IV asphalt
Commonly used for mopping of modified-bitumen sheets
INCREASING SPT

FIGURE 33.8 Types of roofing asphalt and their softening-point temperature (SPT) and relative durability. Type III asphalt is most commonly used in built-up roofs and Type IV in mop-applied modified bitumen roofs.

TYPES OF ROOFING ASPHALT

ASTM specifications divide roofing asphalts into four types: Types I, II, III, and IV. The most important property that distinguishes one type from the other is the *softening-point temperature* (SPT) of asphalt. SPT is the temperature at which asphalt begins to flow. It is directly related to the weathering characteristics of asphalt. The lower the SPT, the more durable the asphalt and the more easily the asphalt will heal any cracks caused by expansion or contraction in roof membrane. Figure 33.8 gives the SPT ranges of the four asphalt types.

The most commonly used asphalt is Type III. It is used as an interply adhesive and as an adhesive to bond insulation to the deck or to bond two layers of insulation together. Because of its lower viscosity, Type III (and also Type IV) can be used to adhere bituminous flashings on vertical surfaces.

Type IV asphalt performs better than Type III, but its lower durability is a deterrent. Type III asphalt is also specified for the flood coat for roofs in warm climates. However, in colder climates (and roof slope permitting), Type I or Type II asphalt should be considered for the flood coat due to its better weathering characteristics. Types III and IV asphalts are available in paper-wrapped kegs, Figure 33.9. Types I and II are available in metal containers because of their lower SPT.

pecialty Products
Wynnewood, Oklahoma
TEL. 1-800-433-6752
ASTM-D312-89
TYPE III

FIGURE 33.9 Types III and IV asphalt are generally available in paper-wrapped kegs.

AMOUNT OF ASPHALT REQUIRED

Approximately 25 lb of asphalt per roof square is recommended for interply moppings, and 60 lb per roof square is suggested for the flood coat. The flood coat is poured on the roof, not mopped on, to provide the large quantity of asphalt required.

BUILT-UP ROOF SURFACING

Because both coal tar and asphalt degrade over time due to their exposure to ultraviolet radiation, the topmost layer in a built-up roof must be protected. Stone aggregate is by far

NOTE

Weight of Aggregate Surfacing

The weight of aggregate surfacing on a built-up roof is generally 400 lb per roof square, that is, 4 lb/ft^2.

the most commonly used protective covering. Apart from protecting the bitumen from ultraviolet radiation, an aggregate surface increases the fire resistance of the roof, protects the membrane from hail impact, and adds weight over the membrane, increasing its resistance to wind uplift.

The aggregate must be a graded aggregate so that most of the particles sink into the bitumen. The average recommended aggregate size is $\frac{3}{8}$ in., with a maximum aggregate size of $\frac{3}{4}$ in. A minimum aggregate weight of 400 lb per roof square is generally recommended.

Water-worn river gravel is an ideal surfacing material because it does not damage the membrane under occasional foot traffic, but crushed stone may be used if the traffic on the roof is minimal. Blast-furnace slag (see Section 18.1) also makes a good surfacing material. The use of lightweight aggregate, which may be dislodged under high wind or rainstorm conditions, is generally discouraged. It may clog the drains and disintegrate under freeze-thaw action.

NOTE

Roof Square

Built-up roof felt rolls are 36 in. wide and 36 ft long. Thus, the area of a roll is 108 ft^2. With a 2-in. head lap and a 6-in. lap at the end of a roll, one roll covers a roof area of 34 in. × 35 ft 6 in., which is approximately equal to 100 ft^2.

In the roofing industry, 108 ft^2 is referred to as a *factory square* and 100 ft^2 is called a *roof square*.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. A low-slope roof is defined as a roof whose slope is less than
- **a.** 1:12.
- **b.** 1.5:12.
- **c.** 2:12.
- **d.** 2.5:12.
- **e.** 3:12.

2. Low-slope roofs are more commonly used than steep roofs.
- **a.** True
- **b.** False

3. Because of the general trend toward *sustainable* and *organic* construction, organic felts are increasingly replacing fiberglass felts in built-up roofs.
- **a.** True
- **b.** False

4. Bitumen-treated fiberglass felt
- **a.** is less porous than bitumen-treated organic felt.
- **b.** is more porous than bitumen-treated organic felt.
- **c.** has the same porosity as bitumen-treated organic felt.
- **d.** none of the above.

5. Which of the following represents an asphalt-treated fiberglass felt?
- **a.** Type II
- **b.** Type III
- **c.** Type IV
- **d.** No. 15
- **e.** No. 30

6. A built-up roof membrane is generally finished with
- **a.** a single-ply roof membrane.
- **b.** aggregate surfacing.
- **c.** a flood coat of bitumen.
- **d.** all of the above.
- **e.** (b) and (c).

7. A roof square implies
- **a.** 1 ft^2 of roof area.
- **b.** 10 ft^2 of roof area.
- **c.** 100 ft^2 of roof area.
- **d.** 1 m^2 of roof area.
- **e.** 10 m^2 of roof area.

8. Asphalt is a waste product obtained from
- **a.** the manufacturing of coal tar.
- **b.** the manufacturing of rubber.
- **c.** petroleum refining.
- **d.** the manufacturing of steel.
- **e.** none of the above.

9. The weight of aggregate surfacing on a built-up roof is generally
- **a.** 5 lb per roof square.
- **b.** 15 lb per roof square.
- **c.** 25 lb per roof square.
- **d.** 40 lb per roof square.
- **e.** 400 lb per roof square.

10. Which of the following built-up roof membranes is more commonly used?
- **a.** Asphalt built-up roof membrane
- **b.** Tar built-up roof membrane

11. Which of the following roofing asphalts is commonly used for interply mopping?
- **a.** Type I
- **b.** Type II
- **c.** Type III
- **d.** Type IV
- **e.** None of the above

33.4 MODIFIED BITUMEN ROOF MEMBRANE

A modified bitumen sheet is similar to built-up roof felt because the waterproofing agent is the bitumen, to which a polymer has been added to modify the bitumen's properties. The polymer's addition to the bitumen improves its characteristics so that the modified bitumen is more pliable and elastomeric compared to the (unmodified) bitumen. The polymer also increases the ultraviolet radiation resistance of the bitumen. Modified bitumen is, therefore, more resistant to cold temperatures and to ultraviolet radiation than the bitumen used in a built-up roof membrane.*

Of the two modified bitumen roof membranes—modified asphalt and modified coal tar—modified asphalt is far more commonly used. The two most common asphalt modifiers are

- Styrene butadiene styrene (SBS)
- Attactic polypropylene (APP)

NOTE

SBS- and APP-Modified Bitumen Sheets

SBS-Modified Bitumen sheet

- Greater flexibility
- Greater resistance to a cold environment

APP-Modified Bitumen Sheet

- Greater resistance to ultraviolet radiation

---

*Regular (unmodified) asphalt and coal tar become relatively brittle in a cold environment. However, this fact does not greatly influence the performance of a built-up roof in cold climates, as is sometimes believed. For instance, the long-term performance of built-up roofs in Canada and the northern United States compares favorably with that of modified bitumen or single-ply roofs.

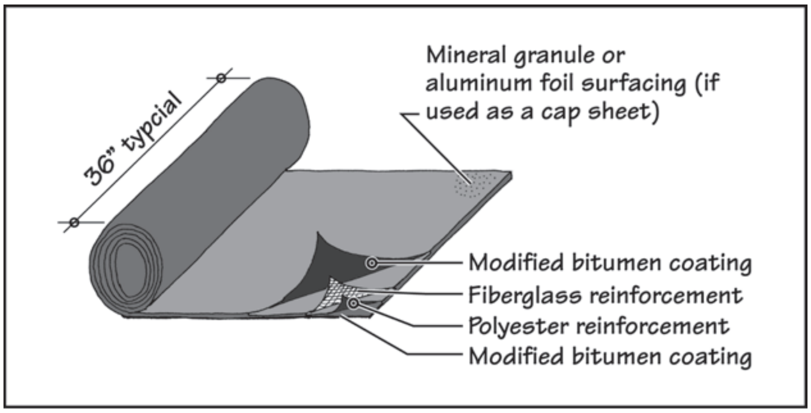


FIGURE 33.10 Anatomy of a modified bitumen membrane with fiberglass and polyester scrims.

The SBS modifier is a synthetic rubber. Therefore, an SBS-modified sheet is more flexible and more resistant to cold temperatures than an APP-modified sheet. APP-modified asphalt has greater resistance to ultraviolet radiation, which gives an APP sheet greater weatherability than an SBS sheet.

A modified bitumen sheet consists of a reinforcing mat, called a *carrier*, which is impregnated and coated with modified bitumen on both sides. The carriers commonly used are polyester or fiberglass scrims or both. A sheet that has both fiberglass and polyester reinforcements is referred to as a *dual-carrier* sheet, Figure 33.10. Most manufacturers make modified bitumen sheets in 36-in. widths, like the built-up roof felt, although the use of 1-m-wide felt is gradually increasing.

Polyester, which is itself a polymer, has high elongation and thus gives pliability to the sheet. It also adds puncture and tear resistance to the sheet, which is important in resisting rooftop traffic and damage caused by roofers' and repairpersons' tools. Fiberglass has very little elongation, but it provides tensile strength and increases the sheet's fire resistance.

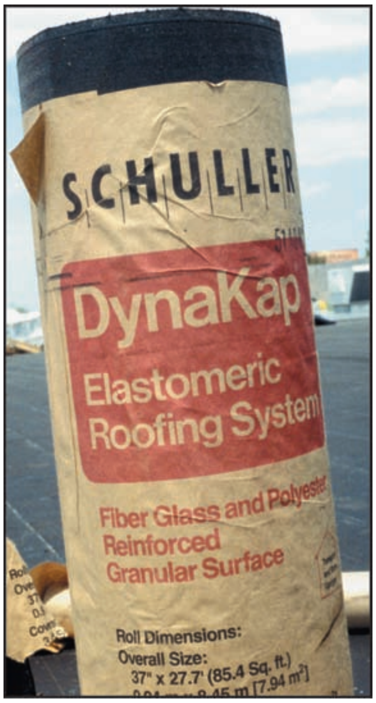
The thickness of a modified bitumen sheet varies from about 100 mil to 200 mil. Therefore, a modified bitumen sheet is much thicker than an asphalt felt, which is only about 30 mil thick. It is also nonporous, unlike the asphalt-treated felt. A thicker modified bitumen sheet is selected if greater strength is required to withstand greater impact and foot traffic. Because of its greater thickness, a modified bitumen roof needs to consist of only two to three sheets to give almost the same performance as four to five plies of a built-up roof.

NOTE

$$1 \text{ mil} = \frac{1}{1{,}000} \text{ in.}$$

A modified bitumen sheet may be either smooth or surfaced with mineral granules or metal foil. A smooth-surfaced sheet is generally used as an intermediate ply or as a base sheet in a two- or three-ply modified bitumen membrane. A mineral granule or foil-faced sheet is used as a cap sheet. The commonly used metal foils are aluminum, copper, and stainless steel.

A cap sheet performs the same function as the flood coat and surfacing in a built-up roof. Mineral granules (typically $\frac{1}{10}$-in. stone chips) and metal foil function as protective covers in a cap sheet. If a smooth-surfaced modified bitumen sheet is used as a cap sheet, it must be protected by a bitumen flood coat and aggregate, like a typical built-up roof.


SCHULLER
DynaKap
Elastomeric Roofing System
Fiber Glass and Polyester Reinforced Granular Surface
Roll Dimensions:
Overall Size:
37" x 27.7' (85.4 Sq. ft.)

A typical SBS-modified granule-surfaced cap sheet roll.

SBS-MODIFIED BITUMEN MEMBRANE

An SBS sheet is typically mop applied with hot asphalt. SBS sheets requiring torch application and, more recently, self-adhering membranes are also available. The low-temperature flexibility (elastomeric nature) of an SBS sheet provides some advantage in colder climates over a conventional built-up roof or an APP-modified bitumen roof.

With hot-asphalt-mopped SBS sheets, Type IV roofing asphalt is commonly used. Type IV asphalt has an application temperature of nearly 500°F—a temperature high enough to soften the SBS-modified asphalt in SBS sheets. (SBS-modified asphalt softens at approximately 350°F.) The amount of asphalt required is the same as for interply moppings in a built-up roof, that is, nearly 25 lb per roof square.

A two- or three-ply SBS membrane gives good performance under most conditions. A two-ply membrane may consist of a smooth-surfaced SBS base sheet covered by a granule-surfaced

EXPAND YOUR KNOWLEDGE

The Terms: Felt, Ply, Membrane, and Sheet

As mentioned in Section 33.3, the individual sheets between bitumen moppings in a built-up roof are referred to as *felts*. A felt and the corresponding layer of bitumen (adhesive) is referred to as a *ply*. An assembly of two or more plies is referred to as a *membrane*. When modified bitumen sheets were first introduced (in the mid-1960s), it was thought that only one modified bitumen sheet would perform as well as an assembly of felts and bitumen moppings in a built-up roof—the built-up roof membrane. Therefore, modified bitumen sheets were referred to as *membranes* and were even included in the single-ply membrane family.

It was subsequently realized that a single sheet of modified bitumen is inadequate and that two or more sheets (plies) are generally needed to provide a reasonable roof. However, each such sheet is referred to as a *membrane* in some roofing literature, which is an incorrect use of the term *roof membrane*. A membrane is the entire waterproofing layer on the roof. It may consist of one ply, as in a single-ply roof membrane; an assembly of four to five plies, as in a built-up roof; or two to three plies, as in a modified bitumen roof.

Similarly, the term *felt*, in roofing vernacular, is reserved for either an organic or fiberglass sheet, typically used in a built-up roof, which together with a bitumen mopping constitutes one built-up roof ply. Other roofing sheets are not referred to as felts. For instance, in a commonly used modified bitumen membrane assembly, consisting of two plies, the first ply is called a *base sheet* and the second ply is called a *cap sheet*. The base sheet is usually a smooth-surfaced modified bitumen sheet, and the cap sheet is a granule-surfaced modified bitumen sheet.

SBS cap sheet. A foil-faced SBS cap sheet may be substituted for a granule-surfaced cap sheet. A three-ply SBS membrane consists of two smooth-surfaced sheets, followed by a mineral or foil-faced SBS cap sheet, Figure 33.11.

BUILT-UP AND SBS HYBRID MEMBRANE

An SBS-modified bitumen sheet can also be combined with a built-up roof membrane to give an SBS and built-up hybrid. Such a membrane may consist of a two- to four-ply conventional built-up roof followed by a granule or foil-faced SBS cap sheet. In place of an SBS cap sheet, a smooth-surfaced SBS sheet with an asphalt flood coat and gravel surfacing may be used, as in a built-up roof, Figure 33.12.

The asphalt for the flood coat is generally the regular (unmodified) roofing asphalt, although SBS-modified asphalt can also be used. SBS-modified asphalt is compatible with (regular) roofing asphalt and can be used with built-up roof felts or with SBS sheets.

APP-MODIFIED BITUMEN MEMBRANE

Just as the addition of an SBS modifier raises the softening-point temperature of asphalt, so does the addition of an APP modifier. In fact, the addition of an APP modifier raises the softening-point temperature of the APP-modified asphalt so much that an APP-modified membrane cannot be hot mopped like an SBS sheet or a built-up roof felt. The application temperature of even Type IV asphalt (nearly 500°F) is not high enough to melt the asphalt in an APP sheet for good adhesion.

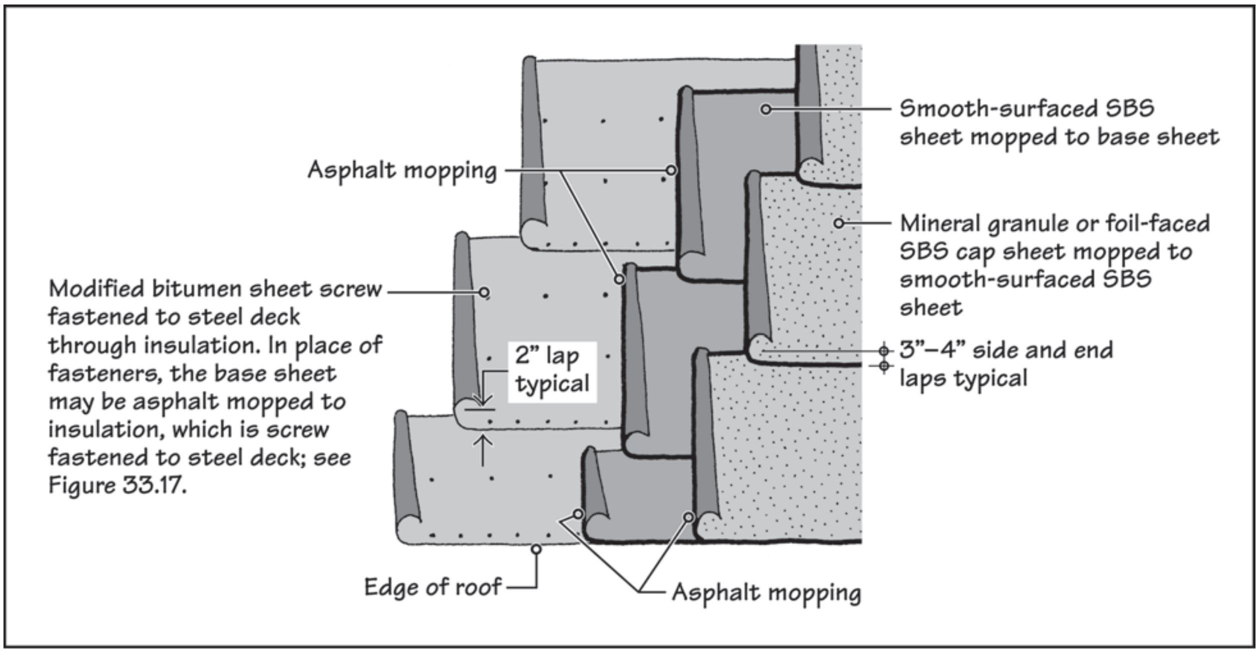

Smooth-surfaced SBS sheet mopped to base sheet
Asphalt mopping
Mineral granule or foil-faced SBS cap sheet mopped to smooth-surfaced SBS sheet
Modified bitumen sheet screw fastened to steel deck through insulation. In place of fasteners, the base sheet may be asphalt mopped to insulation, which is screw fastened to steel deck; see Figure 33.17.
2" lap typical
3"–4" side and end laps typical
Edge of roof
Asphalt mopping

FIGURE 33.11 A three-ply SBS-modified roof membrane consisting of a granule- or foil-faced, SBS-modified bitumen cap sheet and two smooth-surfaced SBS sheets.

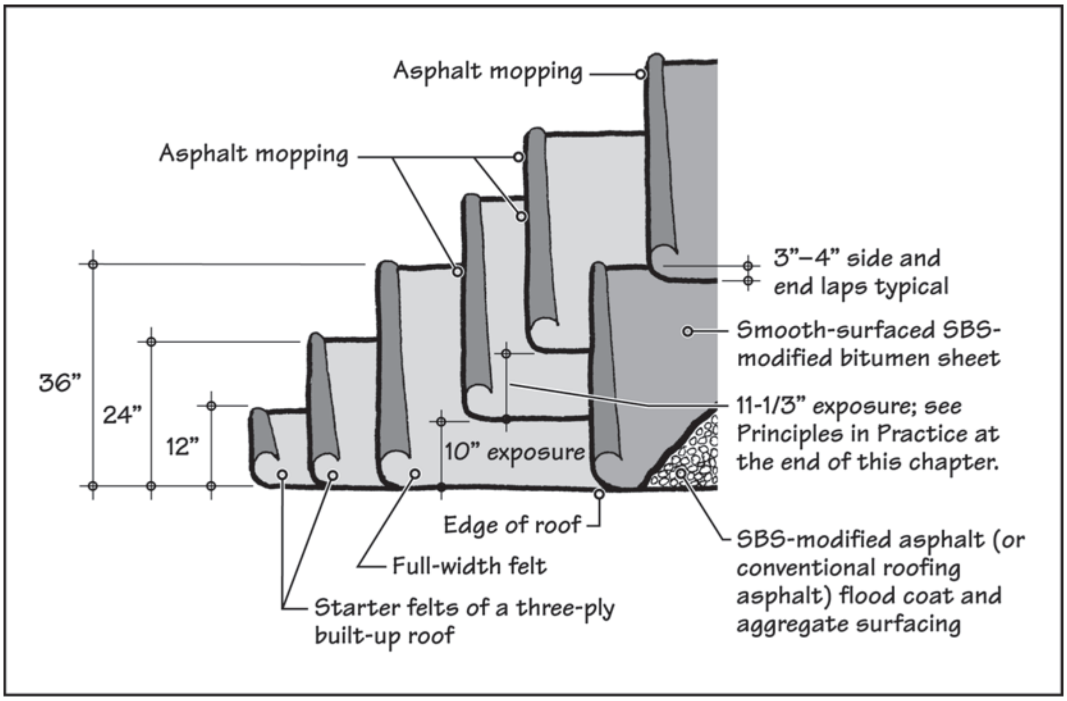

Asphalt mopping
Asphalt mopping
3"–4" side and end laps typical
Smooth-surfaced SBS-modified bitumen sheet
11-1/3" exposure; see Principles in Practice at the end of this chapter.
36"
24"
12"
10" exposure
Edge of roof
Full-width felt
Starter felts of a three-ply built-up roof
SBS-modified asphalt (or conventional roofing asphalt) flood coat and aggregate surfacing

FIGURE 33.12 A built-up and SBS hybrid consisting of a smooth-surfaced SBS-modified bitumen sheet and an aggregate-covered flood coat over a three-ply built-up roof. Note that built-up roof felts are mopped in the shingled format (see Principles in Practice at the end of this chapter).

The most common method of installing an APP sheet is through the open flame of a hand-held propane torch, Figure 33.13, which has a temperature of more than 1,000°F. In this application, the flame is applied to the sheet roll from one end to the other. As the flame melts the modified asphalt on the underside of the sheet, the roll is unwound and pressed down. In this way, the sheet is fully adhered to the substrate. The sheets are usually factory laminated with a thin polyethylene release sheet to prevent adhesion in the roll. The torch burns the polyethylene sheet. Some manufacturers use sand dusting in place of a polyethylene sheet.

An alternative to the hand-held torch is a *dragon wagon*, which consists of a series of propane torch heads mounted on a wheelable cart that also carries the APP sheet roll. A dragon wagon speeds up the installation of an APP sheet but should be used only on a large open roof with few penetrations.

TORCHED MEMBRANE'S SUITABILITY

A torched membrane is suitable in situations where the hot bitumen used in a conventional built-up roof (or an SBS roof) cannot be pumped from the ground to the roof, such as on the roof of a high-rise building. The torched system also has an advantage in cold climates, where keeping the asphalt hot enough between the kettle and the point of application is a problem.

In fact, the torch-adhered, SBS-modified bitumen roof may be preferred for cold regions for the preceding reasons and also because of the greater flexibility of an SBS roof compared with an APP or a built-up roof. However, the open torch used in laying a torchable

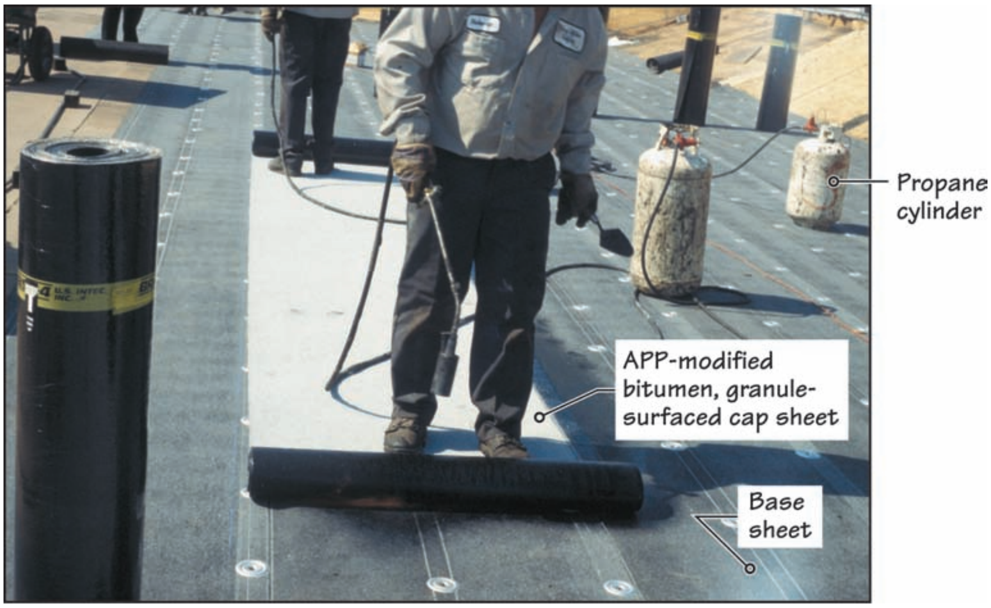

Propane cylinder
APP-modified bitumen, granule-surfaced cap sheet
Base sheet

FIGURE 33.13 A granule-surfaced, APP-modified bitumen cap sheet being adhered to a base sheet with the help of a propane torch. The base sheet has been screw fastened to the underlying steel deck through rigid board foam insulation.

membrane presents a fire hazard, which must be considered before specifying a torched membrane. Fire extinguishers must be available on the roof for any emergency, and personnel need to be left on the roof for a "fire watch" for a few hours after the day's work.

Although an APP sheet has a degree of ultraviolet resistance, a surfacing over it gives additional protection. Mineral granule or foil surfacing on an APP cap sheet adds to its durability. Where practical, an APP roof should be flood coated and covered with gravel for greater durability and fire resistance.

APP and Built-Up Roof Hybrid

A two-layer APP membrane—the first layer, a smooth-surfaced APP sheet, and the top layer, a mineral-surfaced APP cap sheet—can provide an adequate membrane in most situations. Alternatively, an APP cap sheet may be used over two to three plies of built-up roof felt, giving an APP and built-up roof hybrid membrane.

33.5 SINGLE-PLY ROOF MEMBRANE

Although a built-up roof membrane (and, to a smaller extent, a modified bitumen membrane) is constructed on the roof felt by felt, a single-ply roof has only a one-ply membrane and does not require the cumbersome use of hot bitumen. It is easier to lay because it has only one ply.

A single-ply membrane is made of a polymeric material. Because a polymer is a synthetic material, it is capable of a great deal of chemical manipulation by minor changes in one or more of its constituents. Therefore, a large number of polymers are used as roof membranes. However, polymers (plastics), in general, can be divided into two broad categories:

- *Thermosetting polymer (unweldable plastic):* a polymer that does not soften on heating once it is cured into hardness, like a boiled egg. Therefore, the seams in a thermosetting membrane cannot be heat welded but must be adhered together by an adhesive or a double-sided seam tape. The most commonly used thermosetting membrane is EPDM, an acronym that stands for ethylene propylene diene monomer.
- *Thermoplastic polymer (heat-weldable plastic):* a polymer that softens on heating and hardens on cooling over and over again, like butter. Asphalt and coal tar behave like a thermoplastic. A thermoplastic material is heat weldable, which makes the seaming operation relatively easier. However, thermoplastic polymer is not as stretchable as thermosetting polymer. Currently, the most commonly used thermoplastic roof membranes are PVC (polyvinyl chloride) and TPO (thermoplastic polyolefin); TPO is more commonly used than PVC.

Advantages and Disadvantages of a Single-Ply Membrane

By virtue of the material of which it is made, a single-ply membrane is highly flexible and can withstand large elongation before failure. For example, a typical EPDM membrane will stretch 300%–500% of its original length before tearing apart, compared to 50% for an SBS-modified bitumen sheet and 4% for a fiberglass-reinforced built-up roof felt.

For a variety of reasons, a typical single-ply membrane comes in much wider and longer rolls than a built-up roof felt or a modified bitumen sheet, Figures 33.14 and 33.15. Although advantageous (because it reduces the number of lap splices, which reduces lap-failure possibilities), a large roll size also means that roof penetrations are more difficult to work around. Therefore, a single-ply membrane has an advantage on a large roof with few penetrations.

The relative flexibility and the elongation characteristic of a single-ply membrane are useful in climates with a large annual or daily temperature variation. A single-ply membrane (particularly EPDM) retains its elastomeric character even in subzero (Fahrenheit) temperatures. Another advantage of a single-ply membrane is that it does not require aggregate surfacing.

A major disadvantage of a single-ply roof membrane is the absence of second, third, or additional plies. This implies a lack of redundancy in a single-ply roof—a redundancy that is helpful in any waterproofing application. A puncture or split results in a roof leak more readily in a single-ply roof than in a built-up roof because of the greater thickness, multiple plies, and self-healing property of bitumen in a built-up roof.

As stated previously, the overall market share of single-ply membranes is approximately the same as that of built-up or modified bitumen membranes—that is, roughly one-third each. Because EPDM, PVC, and TPO are the more commonly used single-ply membranes, the following discussion relates to them only, although it is general enough to apply to other single-ply membranes as well.

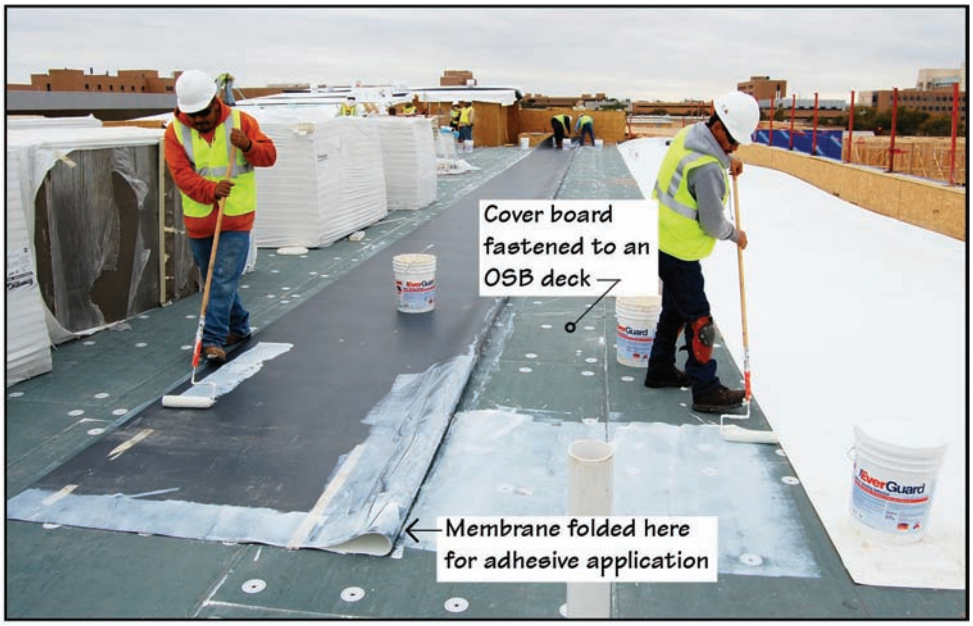

Cover board fastened to an OSB deck
Membrane folded here for adhesive application

FIGURE 33.14 A 10-ft-wide, 60-ft-long single-ply roof membrane being fully adhered to gypsum cover board. The membrane has been folded in the center for the application of adhesive to the membrane's underside. The second worker (on the right-hand side) is applying the adhesive to the cover board. After the application of adhesive to both membrane and cover board, the membrane will be unfolded back, as shown in Figure 33.15.

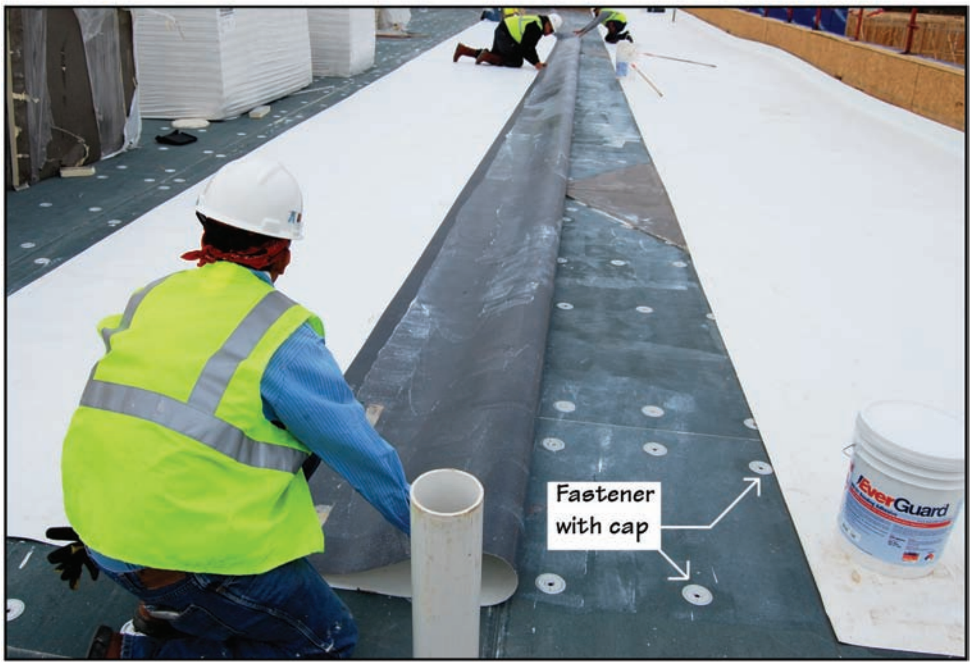


FIGURE 33.15 The image shows the unfolding of the membrane of Figure 33.14 after the adhesive application is complete. After unfolding, the membrane will be pressed down with a heavy roller to obtain its full adhesion to the underlying cover board.

EPDM MEMBRANE

Because EPDM is a synthetic rubber, it is essentially similar to the material used in automobile tires. Firestone is, therefore, one of the major EPDM membrane manufacturers. The typical thickness of an EPDM membrane is 45 mil–60 mil, although some manufacturers make a thicker membrane for use where higher puncture and tear resistance are needed.

EPDM polymer lacks inherent fire resistance, but fire-resistive EPDM membranes are available. However, with a loose-laid, ballasted EPDM roof, a non-fire-resistive membrane may be specified because the ballast will provide the fire resistance. Because EPDM is a synthetic rubber (with its consequent flexibility), its use is more common in colder climates of North America. In warmer climates and in response to sustainability considerations, several architects and roof consultants specify white membranes, which are produced more economically in PVC or TPO. The membrane shown in Figures 33.14 and 33.15 is a white single-ply roof membrane.

PVC MEMBRANE

PVC, the most versatile plastic, is available in two types. Rigid PVC is used for pipes, siding, and window sashes. Soft, pliable PVC is used in shower curtains, raincoats, electrical wire

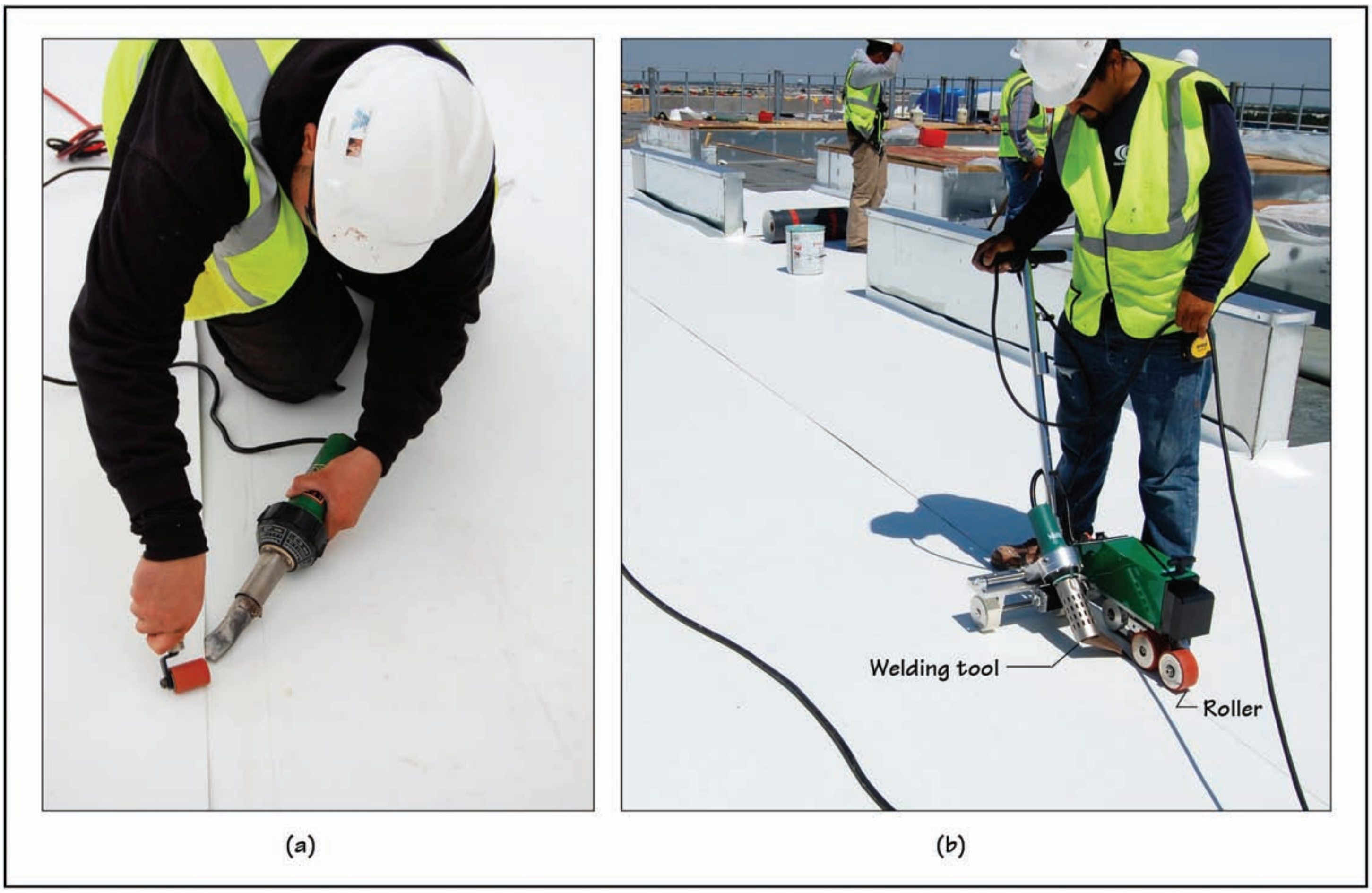


FIGURE 33.16 **(a)** A roofer welds the seams of a white TPO roof membrane with a hand-held welding tool, which has a flat nozzle supplying hot air between the seams. Simultaneous with the welding operation, the roofer presses down the fused seams with a roller. **(b)** A self-propelled hot-air welding machine (with welding tool and roller combined) that welds and presses the seams is an alternative to the hand-held welding tool. The machine speeds the welding process.

insulation, and roof membranes. Softness and flexibility—properties that are necessary for a roofing membrane—are obtained through the addition of a plasticizer. However, despite the addition of a plasticizer, a PVC membrane, though flexible, is far less stretchable than an EPDM membrane.

The primary advantage of a PVC membrane is that the seams in the membrane can be heat fused. A simple tool, such as that shown in Figure 33.16, which supplies hot compressed air, is all that is needed to fuse the seams. This makes roof installation much easier and more economical compared to EPDM roofs, in which the seams must be joined together with a double-sided tape.

Another advantage of PVC is its inherent fire resistance, which is provided by its chlorine atom. PVC membranes are generally used in 45-mil to 80-mil thickness. They are available in several colors, although white and gray are most common.

EXPAND YOUR KNOWLEDGE

EPDM, PVC, and TPO Membranes Compared

Criterion	EPDM	PVC	TPO
Lap-seam attachment	Two-sided tape or contact adhesive	Seams heat welded	Seams heat welded
Fire resistance	Fire-resistive EPDM available	Inherently good	Fire-resistive TPO available
white-sheet availability	Available	More easily made	More easily made
Resistance to ultraviolet radiation	Good for black EPDM	Good	Good
Compatibility with insulation	Compatible with most insulations	Incompatible with polystyrene foam due to plasticizers	Compatible with most insulations
Compatibility with asphalt	Incompatible	Incompatible	Incompatible

TPO MEMBRANE

Like PVC, TPO is also thermoplastic. Therefore, it has the same advantage over EPDM as PVC, that is, the heat weldability of its seams. Although less flexible than EPDM, TPO is inherently more flexible than PVC, not requiring the addition of plasticizers in its chemical formulation.

This makes TPO more economical than PVC; also, there is no concern about the gradual evaporation of plasticizers (as with PVC), which causes the PVC membrane to lose its flexibility over time. Thus, TPO combines the advantages of EPDM and PVC, which explains the increasing popularity of TPO among the single-ply membranes.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

12. which of the following modified bitumen membranes is more elastomeric?
a. SBS-modified bitumen
b. APP-modified bitumen

13. Which of the following modified bitumen membranes is generally torch applied?
a. SBS-modified bitumen
b. APP-modified bitumen

14. Which of the following roofing asphalts is commonly used for mopping an SBS-modified bitumen membrane?
a. Type I
b. Type II
c. Type III
d. Type IV
e. SBS-modified asphalt

15. A dragon wagon is used in laying
a. a single-ply roof membrane.
b. a modified bitumen roof membrane.
c. a built-up roof membrane.
d. all of the above.
e. none of the above.

16. EPDM is a thermosetting plastic.
a. True
b. False

17. The lap seams in an EPDM roof membrane are typically sealed by
a. heat welding.
b. liquid adhesives.
c. single-sided tape.
d. double-sided tape.
e. any one of the above.

18. The lap seams in a PVC roof membrane are typically sealed by
a. heat welding.
b. liquid adhesives.
c. single-sided tape.
d. double-sided tape.
e. any one of the above.

19. The lap seams in a TPO roof membrane are typically sealed by
a. heat welding.
b. liquid adhesives.
c. single-sided tape.
d. double-sided tape.
e. any one of the above.

20. Of the two single-ply roof membranes, EPDM and PVC, PVC is generally
a. more flexible and more fire resistant.
b. less flexible but more fire resistant.
c. more flexible but less fire resistant.
d. less flexible and less fire resistant.

33.6 ATTACHMENT OF LOW-SLOPE ROOF COMPONENTS

The insulation used with built-up and modified bitumen roofs is a polyiso board topped with a perlite board or a high-density fiberboard as cover board. The typical thickness of cover board is $\frac{3}{4}$ in. to 1 in. The thickness of the polyiso board is a function of the amount of R-value required. Figure 33.17 illustrates the anatomy of such a roof and how various components are attached.

As Figure 33.17 shows, the insulation is attached to a steel deck with screws. For a concrete deck, the insulation may be adhered with bitumen mopping, provided that the deck is dry. If the deck is not fully dry, the moisture in the deck will blister through bitumen as steam, reducing attachment strength. Nonbituminous adhesives are available that do not require a fully dry concrete deck. Continuous adhesive beads or spots of adhesives are generally used with such adhesives, depending on the roofing system manufacturer.

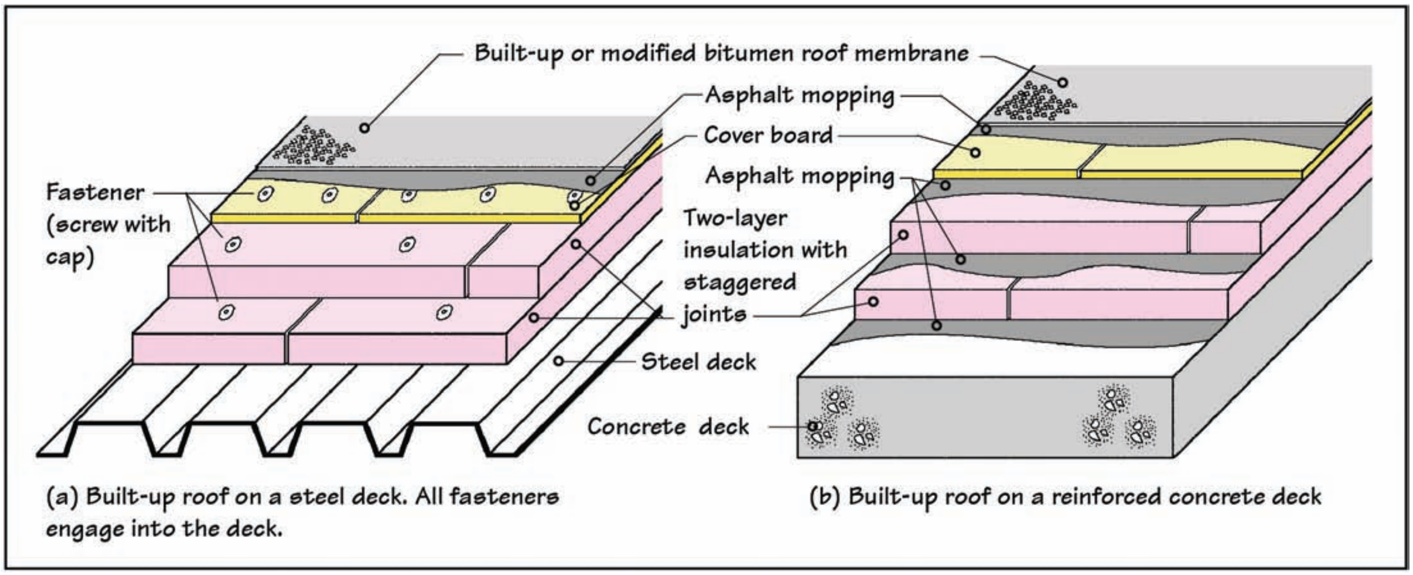
ATTACHMENT OF COMPONENTS IN A SINGLE-PLY ROOF MEMBRANE

Whereas built-up and modified bitumen membranes are attached through bitumen mopping, a single-ply membrane (EPDM, PVC, and TPO) is attached using one of the following three systems:

- Fully adhered
- Mechanically fastened
- Ballasted

FULLY ADHERED SYSTEM OF SINGLE-PLY MEMBRANE ATTACHMENT

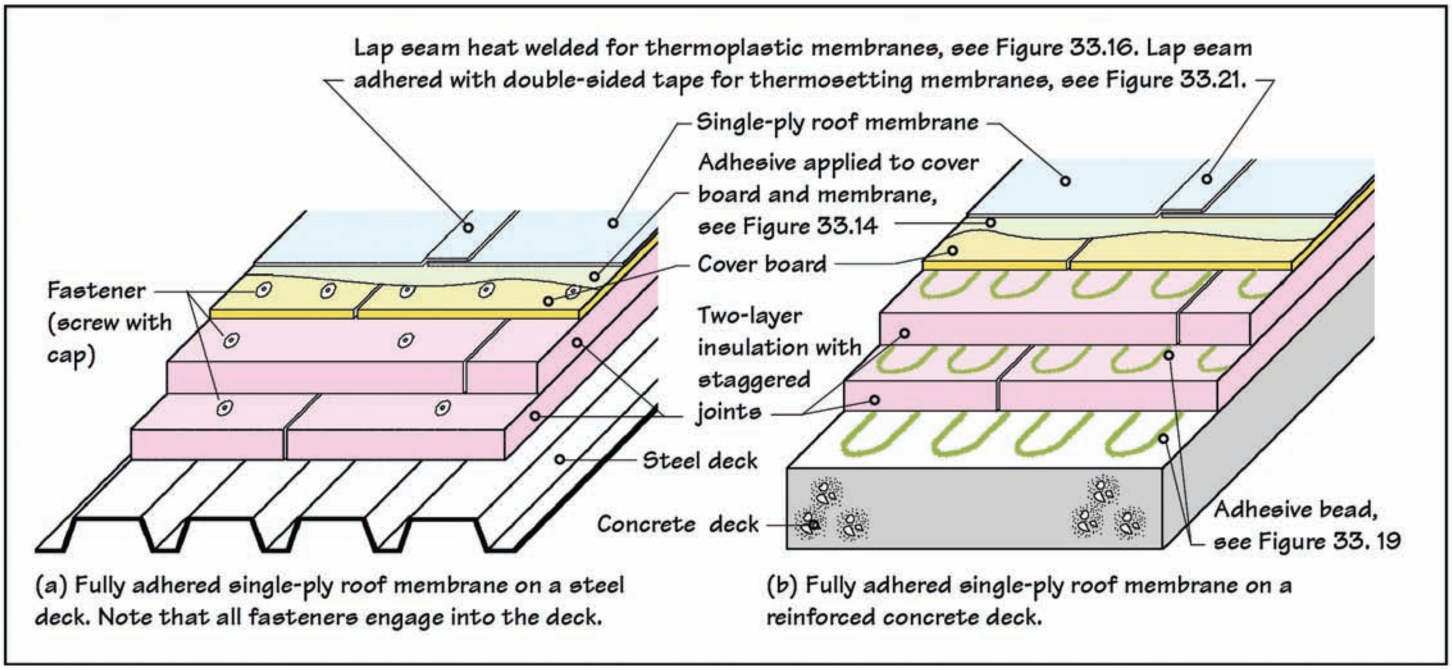
With a fully adhered single-ply membrane, manufacturer-provided adhesive is used on the cover board and the underside of the entire membrane, Figure 33.18 (see also Figures 33.14 and 33.15). The adhesion of cover board and insulation to a concrete deck is accomplished using adhesive beads, Figure 33.19. After the membrane has been adhered, the laps


Built-up or modified bitumen roof membrane
Asphalt mopping
Cover board
Asphalt mopping
Fastener (screw with cap)
Two-layer insulation with staggered joints
Steel deck
Concrete deck

(a) Built-up roof on a steel deck. All fasteners engage into the deck.

(b) Built-up roof on a reinforced concrete deck

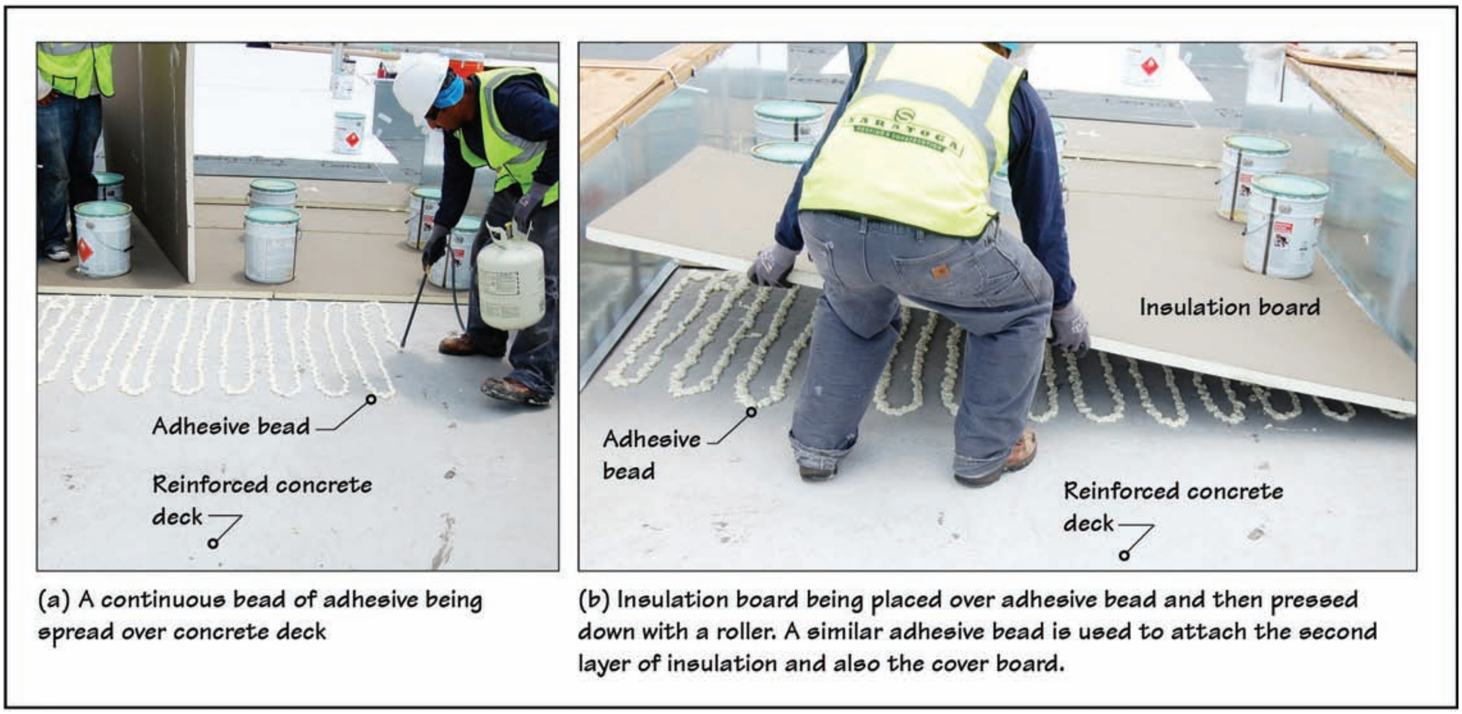
FIGURE 33.17 Anatomy of a built-up or a modified bitumen roof on steel and concrete decks, illustrating the attachment of various components.


Lap seam heat welded for thermoplastic membranes, see Figure 33.16. Lap seam adhered with double-sided tape for thermosetting membranes, see Figure 33.21.
Single-ply roof membrane
Adhesive applied to cover board and membrane, see Figure 33.14
Cover board
Fastener (screw with cap)
Two-layer insulation with staggered joints
Steel deck
Concrete deck
Adhesive bead, see Figure 33. 19

(a) Fully adhered single-ply roof membrane on a steel deck. Note that all fasteners engage into the deck.

(b) Fully adhered single-ply roof membrane on a reinforced concrete deck.

FIGURE 33.18 Anatomy of a fully adhered single-ply roof on steel and concrete decks, showing the attachment of various components.


Adhesive bead
Reinforced concrete deck
Insulation board
Adhesive bead
Reinforced concrete deck

(a) A continuous bead of adhesive being spread over concrete deck

(b) Insulation board being placed over adhesive bead and then pressed down with a roller. A similar adhesive bead is used to attach the second layer of insulation and also the cover board.

FIGURE 33.19 Application of a continuous adhesive bead to adhere roof components on a reinforced-concrete deck, refer to Figure 33.18.

between adjacent membrane sheets are joined with a double-sided tape if it is a thermosetting membrane. With a thermoplastic membrane, the seams are heat welded, as shown in Figure 33.16.

A fully adhered single-ply membrane system is labor intensive compared to a mechanically fastened or ballasted single-ply system. However, the system is particularly well suited to high-wind regions.

MECHANICALLY FASTENED ATTACHMENT SYSTEM FOR A SINGLE-PLY MEMBRANE

In a mechanically fastened system, the membrane is laid after the cover board and insulation have been anchored to the deck, Figure 33.20. The fastening of the insulation and cover board to the deck is nominal—to hold them in place until the membrane has been anchored. The spacing of fasteners for the anchorage of membrane to the deck is a function of the wind uplift on the roof.

The membrane-fastening system consists of screws and a continuous bar (referred to as a *batten bar* in the industry) through which the screws are applied, Figure 33.21(a). The batten bar, typically made of metal or plastic, is covered over by double-sided tape in a lap seam in a thermosetting membrane, such as EPDM. (In a thermoplastic membrane such as PVC and TPO, the lap seams are heat welded.)

Intermediate fasteners and the batten bar, which are not within the seams, are covered with self-adhesive splice tape, Figure 33.21(b). Some manufacturers provide individual plates instead of batten bars for their systems.

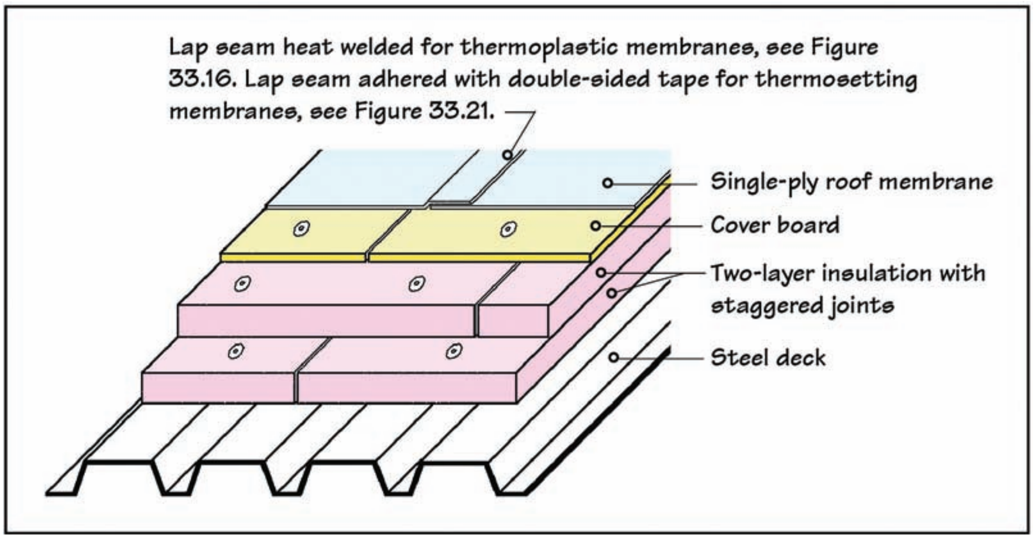

Lap seam heat welded for thermoplastic membranes, see Figure 33.16. Lap seam adhered with double-sided tape for thermosetting membranes, see Figure 33.21.
Single-ply roof membrane
Cover board
Two-layer insulation with staggered joints
Steel deck

FIGURE 33.20 Anatomy of a mechanically fastened single-ply roof on steel and concrete decks, showing the attachment of various components. Note that mechanical fastening is used only with steel or wood decks.

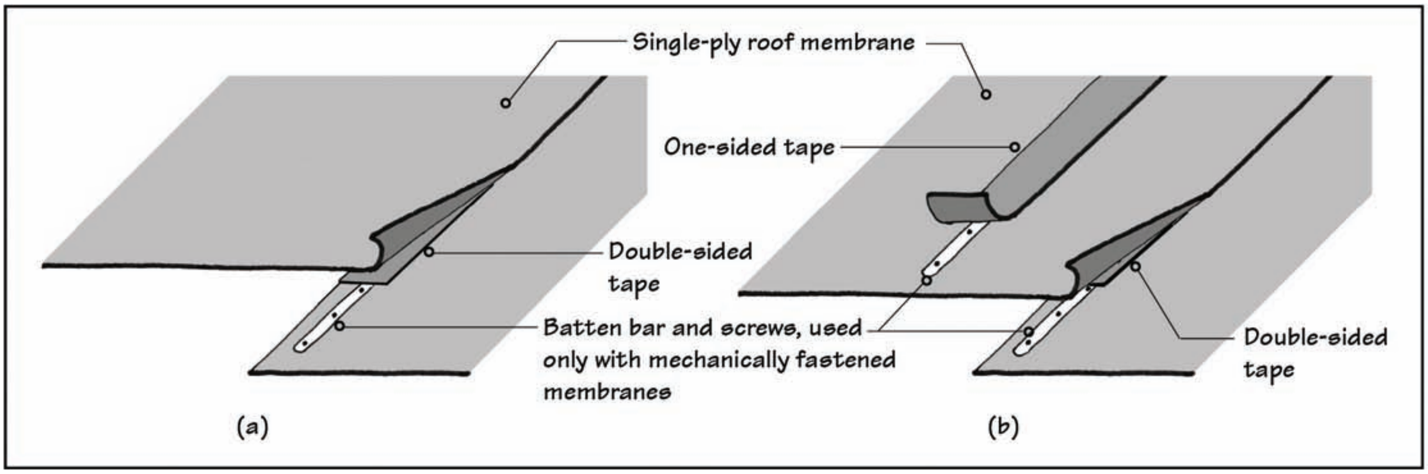

Single-ply roof membrane
One-sided tape
Double-sided tape
Batten bar and screws, used only with mechanically fastened membranes
Double-sided tape
(a)
(b)

FIGURE 33.21 **(a)** The lap seams in a thermosetting single-ply roof membrane are adhered together using a double-sided tape. The batten bar shown is used only with mechanically fastened membranes, not with fully adhered membranes. **(b)** Where a mechanically fastened membrane requires fastening in areas other than the seams, a batten bar covered with one-sided tape is used in the case of a thermosetting membrane. In the case of a thermoplastic membrane, the tape is heat welded.

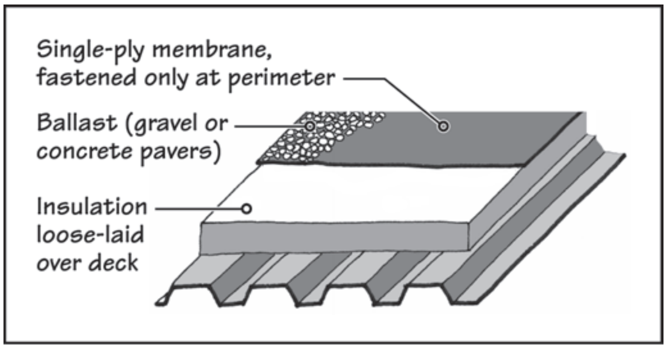

Single-ply membrane, fastened only at perimeter
Ballast (gravel or concrete pavers)
Insulation loose-laid over deck

FIGURE 33.22 Loose-laid, ballasted single-ply membrane system. Note that the insulation is not fastened to the roof deck.

Under the effect of wind, a mechanically fastened system is subjected to concentrated loads at the fasteners. This is unlike a fully adhered system, in which the loads are distributed over the entire membrane. Wind may make the mechanically fastened membrane flutter, causing its premature failure at the fasteners. Therefore, care should be taken in specifying a mechanically fastened system in a high-wind location.

LOOSE-LAID BALLASTED SYSTEM OF SINGLE-PLY MEMBRANE ATTACHMENT

In a loose-laid ballasted system, the entire membrane is laid loose over the insulation, followed by a loose-laid single-ply membrane, Figure 33.22. The lap seams are adhered together using a double-sided tape (thermosetting membrane) or a heat-welded thermoplastic membrane. The membrane is anchored to the deck only at the roof perimeter, curbs, and penetrations. The entire membrane is then covered with ballast, Figure 33.23.

Ballast generally consists of river-worn gravel ($1\frac{1}{10}$- to 2-in. particle size). The use of crushed stone is discouraged because it can puncture the membrane under foot traffic. The weight of the gravel required varies with the wind uplift on the membrane. Concrete pavers may also be used instead of gravel.

The ballasted system is the most economical single-ply system. The ballast adds to fire resistance and weatherability. The system is recommended only for roofs of low-rise buildings in low-wind regions. Because the dead load of ballast is high, the deck must be structurally adequate to withstand the ballast load.

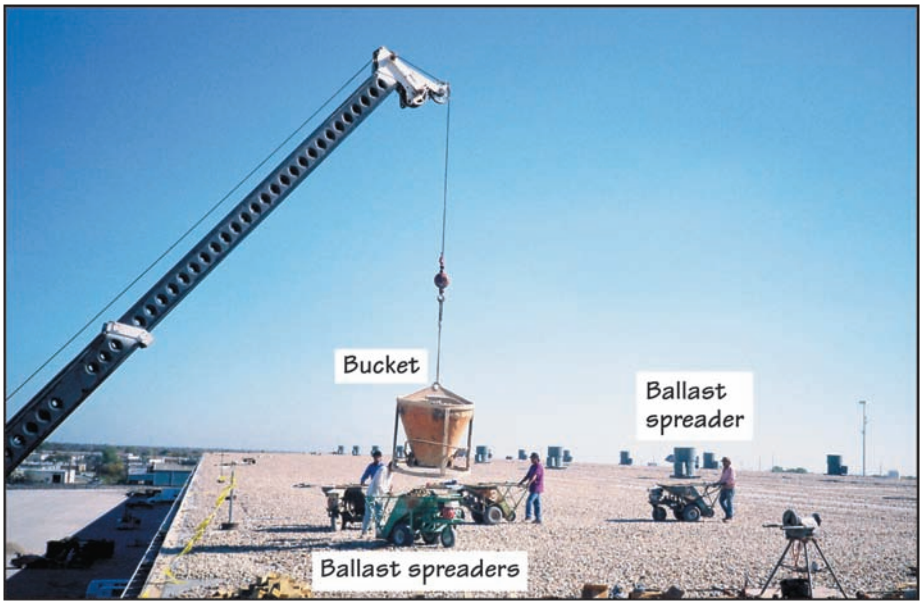


FIGURE 33.23 In a loose-laid, ballasted single-ply membrane system, the ballast is generally brought onto the roof using a crane and buckets. Ballast spreaders are then used to spread the ballast on the roof.

33.7 INSULATING CONCRETE AND MEMBRANE ATTACHMENT

A low-slope roof insulation (other than the rigid boards) is lightweight insulating concrete or foamed concrete. As described in Chapter 5 (Principles in Practice), insulating concrete or foamed concrete is poured over a roof deck in wet format. When the concrete hardens, it becomes monolithic with the deck.

INSULATING CONCRETE

Where insulating concrete is used over a steel deck, the use of a slotted (i.e., perforated) deck is recommended. The perforations in the deck allow the moisture in the concrete to gradually vent out from the underside of the deck by the building's heating and cooling system. Therefore, the roof membrane can be installed as soon as the concrete has become sufficiently hard to hold the fasteners, even though it may not have fully dried.

After the insulating concrete has hardened (typically after three to five days), an asphalt-treated base sheet (preferably a mineral-granule-faced base sheet) is fastened to the concrete as a substrate for a built-up or modified bitumen roof. Special fasteners have been developed by the industry to fasten the base sheet, which can simply be driven into the insulating concrete, Figure 33.24. The fasteners flare as they penetrate into the concrete, Figure 33.25.

After the base sheet has been fastened, the built-up roof or modified bitumen membrane is mopped to the base sheet. A single-ply membrane may also be installed over insulating concrete, but the manufacturers of insulating concrete recommend consulting with the manufacturers of single-ply membranes for compatibility, and so on.

Because below-the-deck venting cannot be provided in a reinforced-concrete or precast-concrete deck, the use of insulating concrete on such decks requires that the insulating concrete be so dry that it does not create water vapor problems in the roofing membrane.

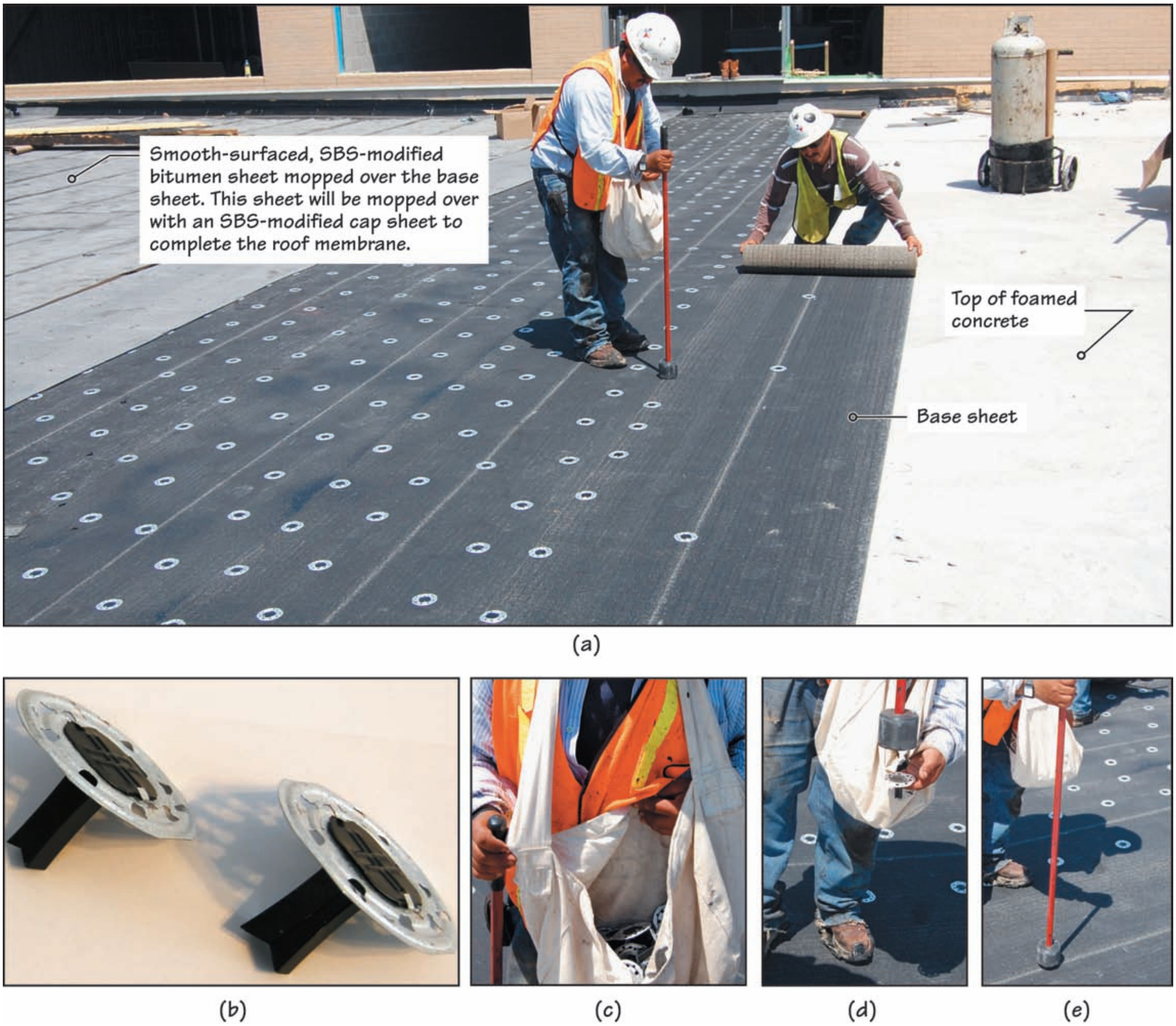

Smooth-surfaced, SBS-modified bitumen sheet mopped over the base sheet. This sheet will be mopped over with an SBS-modified cap sheet to complete the roof membrane.
Top of foamed concrete
Base sheet
(a)
(b)
(c)
(d)
(e)

FIGURE 33.24 **(a)** One roofer unrolls the base sheet, aligning it with the adjacent, already laid base sheet, and another roofer drives the fasteners into the foamed concrete. **(b)** Close-up of a fastener. **(c)** A roofer with a pouch full of fasteners. **(d)** The roofer attaches the fastener to the head of the magnetic driver, and then orients and holds the fastener perpendicular to the roofing surface. **(e)** A vertical tamping motion sets the fastener securely into the concrete.

A major advantage of insulating concrete is that roof slope can easily be provided in the insulation, even if the roof deck is dead level. This is done by using expanded polystyrene (EPS) boards of different thicknesses to create a stairstepped pattern, Figure 33.26. Providing slope over a dead-level deck with tapered rigid board insulation is expensive and complicated. Insulating concrete is also well suited for decks that have a complex slope geometry.

FOAMED CONCRETE

As explained in Chapter 5 (Principles in Practice), foamed concrete, also called *cellular concrete*, is a nonaggregate (insulating) concrete that consists of Portland cement, water, and a liquid foaming concentrate. Foamed concrete requires only one-third the amount of water used in insulating concrete. Therefore, foamed concrete does not need a slotted metal deck, although its use is preferred. The other details, such as fastening a base sheet, stairstepping EPS boards for roof slope, and so on, are similar to those used with insulating concrete.

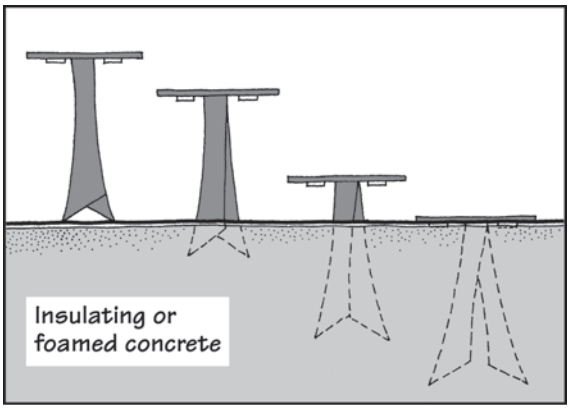

Insulating or foamed concrete

FIGURE 33.25 The fastener flares as it is driven into the concrete. (Sketch adapted from that of ES Products, Inc.)

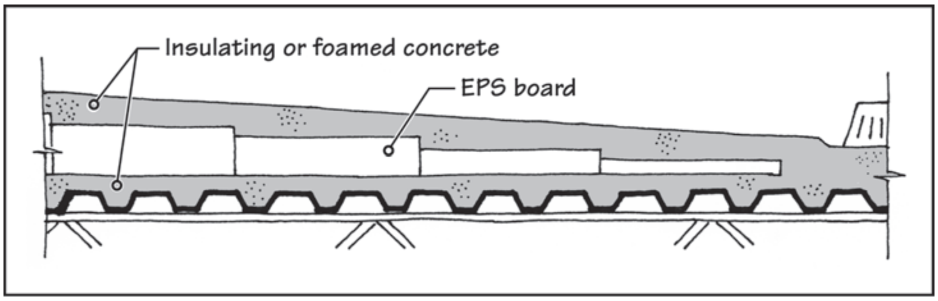


FIGURE 33.26 Section through a roof showing a stairstepped EPS board pattern to achieve a slope on a dead-level roof deck.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

21. Perlite board (as cover board), sandwiched between the insulation and the roof membrane, is generally used with
- **a.** an asphalt-mopped membrane.
- **b.** a fully adhered single-ply membrane.
- **c.** a mechanically fastened single-ply membrane.
- **d.** a loose-laid, ballasted single-ply membrane.

22. The cover board generally used between a single-ply roof membrane and rigid board insulation is
- **a.** iso board.
- **b.** specially treated perlite board.
- **c.** glass-fiber-reinforced gypsum board.
- **d.** extruded polystyrene board.
- **e.** none of the above.

23. A mechanically fastened single-ply roof membrane is generally used with
- **a.** steel roof decks.
- **b.** reinforced-concrete decks.
- **c.** precast-concrete decks.
- **d.** none of the above.

24. A loose-laid ballasted roof is generally used with
- **a.** a built-up roof membrane.
- **b.** a modified bitumen membrane.
- **c.** a single-ply membrane.
- **d.** all of the above.

25. For a building located in a high-wind region, which of the following roof systems is most suitable?
- **a.** Loose-laid ballasted single-ply system
- **b.** Fully adhered single-ply system
- **c.** Mechanically fastened single-ply system
- **d.** Gravel-covered built-up roof
- **e.** Protected membrane system

26. With a steel deck topped with lightweight insulating concrete, the commonly used board insulation is
- **a.** iso board.
- **b.** polyurethane board.
- **c.** expanded polystyrene (EPS) board.
- **d.** not used with insulating concrete.

27. A slotted steel roof deck is mandated for use with
- **a.** all rigid board insulations.
- **b.** lightweight insulating concrete.
- **c.** foamed concrete.
- **d.** none of the above.

33.8 LOW-SLOPE ROOF FLASHINGS

The termination of a roof, which generally occurs over a wall, requires careful detailing. The wall either stops below the roof, in which case the roof terminates in a free edge (requiring a guard edge), or projects above the roof as a parapet wall. In either case, the differential movement between the roof and the wall, and the higher wind loads at roof terminations, increase the stresses in a roof membrane at a wall-roof junction. Additional strength is, therefore, required at a roof-wall junction, which is provided by a special sheet material called *flashing*. Flashing also helps to integrate the roof membrane with the wall and further waterproofs the wall-roof junction, which is more vulnerable to leakage than the field-of-roof, which is the area of the roof that is not a roof perimeter, corner, or termination.

Flashing is also required around penetrations in the roof, such as roof drains, gutters, vent and plumbing stacks, curbs below skylights and rooftop equipment, expansion joints, and area dividers.

Flashings may be divided into three basic types, Figure 33.27:

- Base flashings
- Curb flashings
- Flange flashings

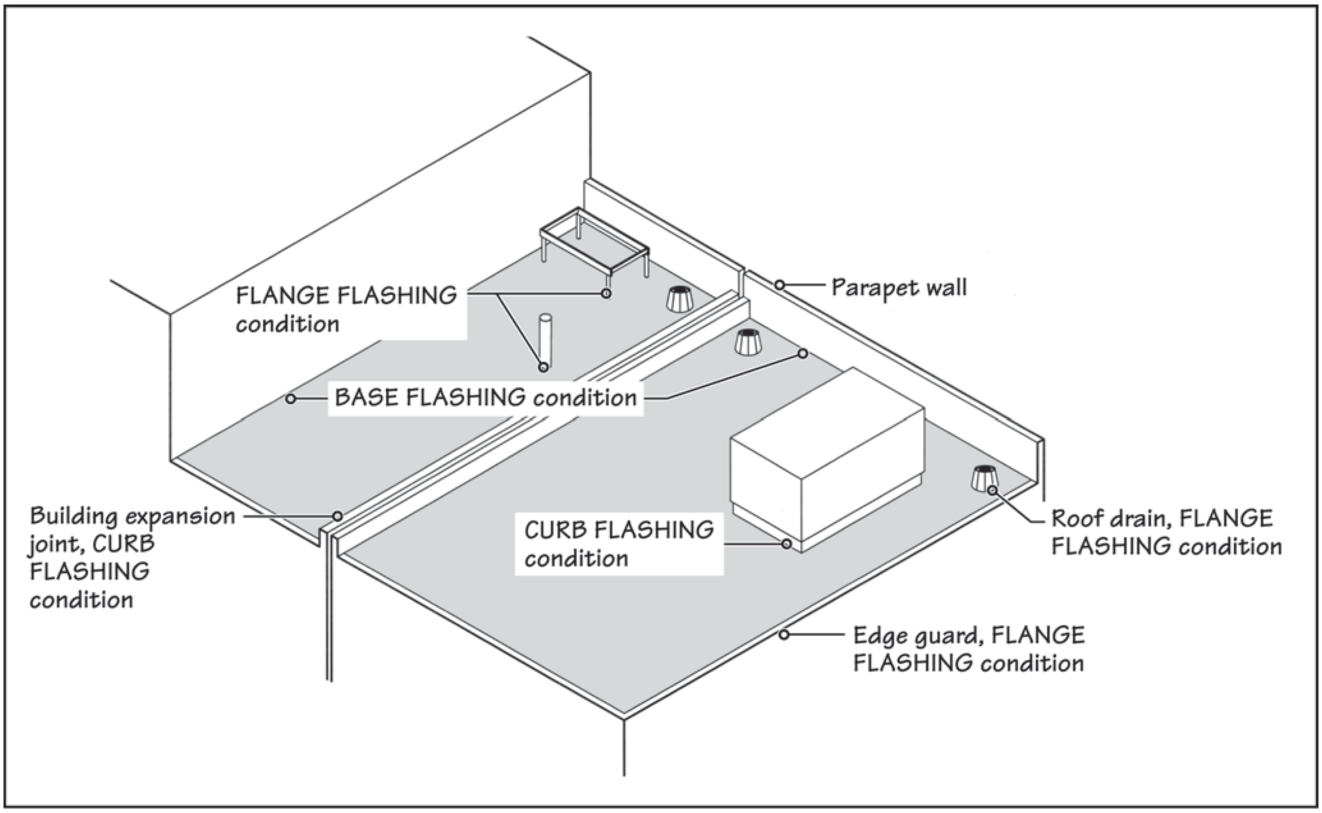

FLANGE FLASHING condition
Parapet wall
BASE FLASHING condition
Building expansion joint, CURB FLASHING condition
CURB FLASHING condition
Roof drain, FLANGE FLASHING condition
Edge guard, FLANGE FLASHING condition

FIGURE 33.27 Three types of roof flashing: base flashing, curb flashing, and flange flashing.

33.9 BASE FLASHING DETAILS

Base flashing occurs at the junction of a roof and a wall that rises above the roof, such as a parapet wall. Five important components of base flashing details are:

- Membrane base flashing
- Perimeter wood nailers
- Cants (required only with built-up and modified bitumen membranes)
- Counterflashing
- Parapet coping

Figure 33.28 illustrates the principles of detailing a base flashing against a low-height parapet (up to about 2 ft high) where the roof deck is supported by a bearing wall.

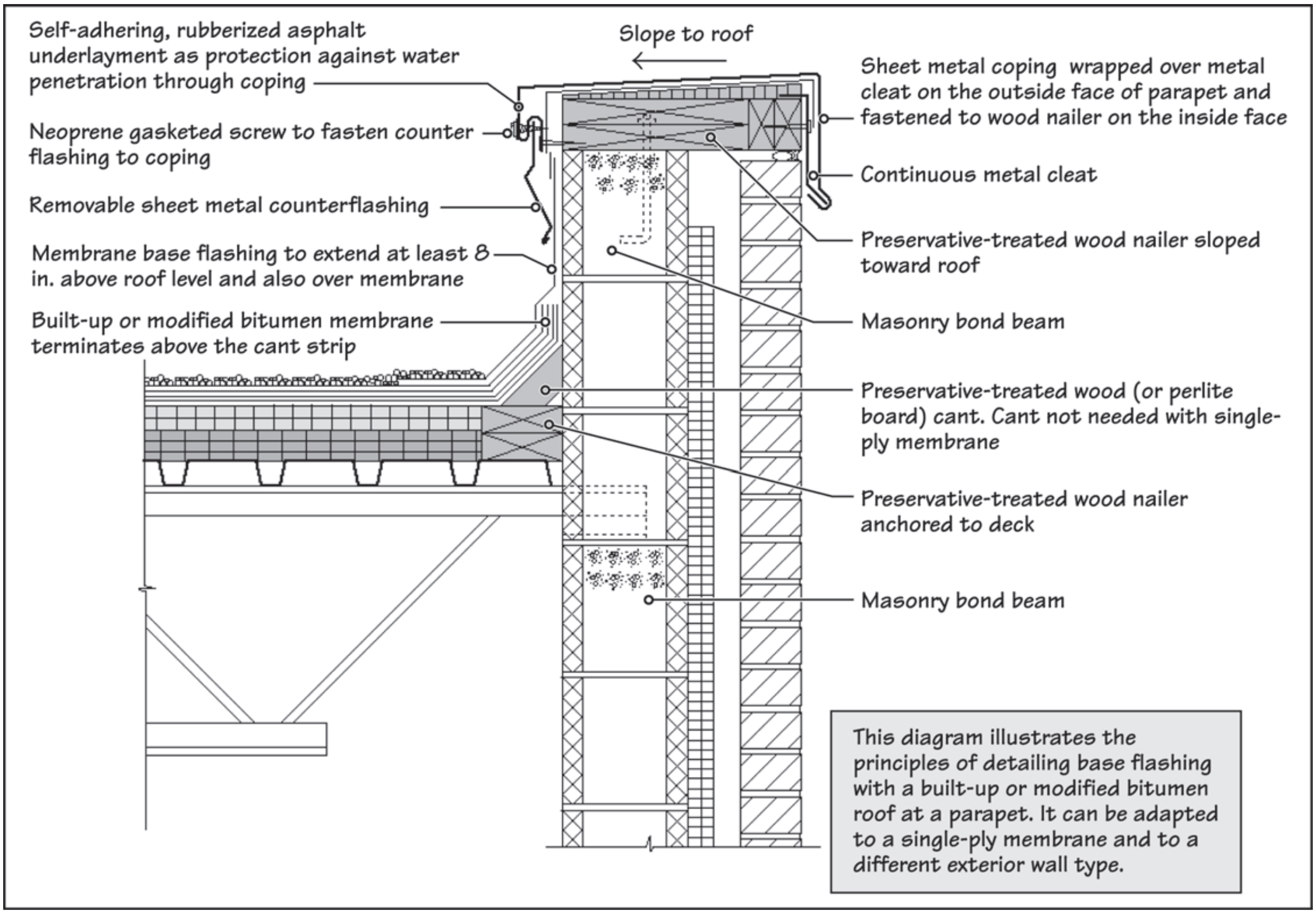
Figure 33.29 illustrates the same principles, but the roof deck is supported on a structural frame (and not by a bearing wall). In this case, the detail must allow differential movement between the exterior wall and the roof, which is provided for separating the roof from the wall at the base flashing level. Base flashing details for a high parapet are essentially similar but are a little more complex [Ref. 33.1].

MEMBRANE BASE FLASHING

Membrane base flashing provides additional reinforcement to the roof membrane and extends the waterproofing ability of the roof to the highest anticipated water level (8 in. minimum is recommended). Membrane flashing also provides additional waterproofing at the roof-wall junction, which, being under greater stress, is more prone to leakage than the field-of-roof.

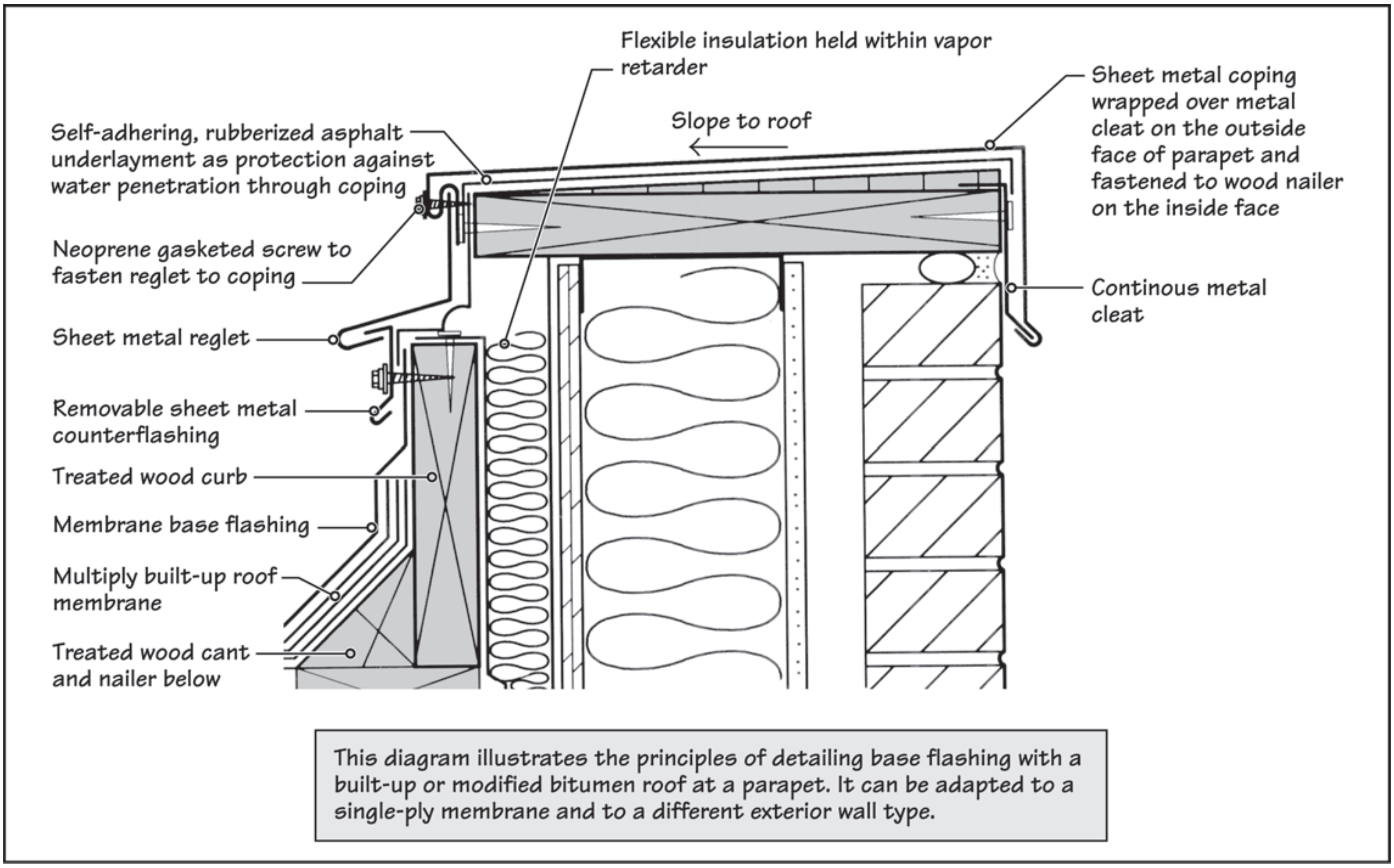
Membrane base flashing must have adequate strength and pliability to withstand minor movement between the wall and the roof. Therefore, the most commonly used membrane base flashing material with a built-up roof is an SBS-modified bitumen sheet. An SBS membrane base flashing is also used with an SBS-modified bitumen roof. An SBS-modified membrane base flashing is generally a mineral-granule-surfaced sheet. Mineral granules protect the flashing against weathering. This is helpful because gravel protection is not available on the vertical portion of membrane base flashing.

Torch-applied flashing sheets are also used, typically with a torch-applied roof membrane. A single-ply flashing material is used with a single-ply roof membrane.


Self-adhering, rubberized asphalt underlayment as protection against water penetration through coping
Slope to roof
Sheet metal coping wrapped over metal cleat on the outside face of parapet and fastened to wood nailer on the inside face
Neoprene gasketed screw to fasten counter flashing to coping
Continuous metal cleat
Removable sheet metal counterflashing
Preservative-treated wood nailer sloped toward roof
Membrane base flashing to extend at least 8 in. above roof level and also over membrane
Masonry bond beam
Built-up or modified bitumen membrane terminates above the cant strip
Preservative-treated wood (or perlite board) cant. Cant not needed with single-ply membrane
Preservative-treated wood nailer anchored to deck
Masonry bond beam

This diagram illustrates the principles of detailing base flashing with a built-up or modified bitumen roof at a parapet. It can be adapted to a single-ply membrane and to a different exterior wall type.

FIGURE 33.28 Base flashing and parapet coping details where the roof deck is supported by an exterior bearing wall.


Flexible insulation held within vapor retarder
Slope to roof
Sheet metal coping wrapped over metal cleat on the outside face of parapet and fastened to wood nailer on the inside face
Self-adhering, rubberized asphalt underlayment as protection against water penetration through coping
Neoprene gasketed screw to fasten reglet to coping
Continous metal cleat
Sheet metal reglet
Removable sheet metal counterflashing
Treated wood curb
Membrane base flashing
Multiply built-up roof membrane
Treated wood cant and nailer below

This diagram illustrates the principles of detailing base flashing with a built-up or modified bitumen roof at a parapet. It can be adapted to a single-ply membrane and to a different exterior wall type.

FIGURE 33.29 Base flashing and parapet coping details where the roof deck is supported by the structural frame and the exterior wall is nonbearing.

PERIMETER WOOD NAILERS AND CANTS

Preservative-treated wood nailers are generally used at the base. Nailers add strength and provide a nailable surface to which the membrane and flashing are fastened.

Because bituminous materials are relatively brittle, they cannot be bent to form a 90° angle since they will crack during service. A cant strip is, therefore, provided at the base. Cant strips may be of pressure-treated wood or of a rigid insulating material, such as perlite board. Perlite-board cant is generally adhered to the nailer.

COUNTERFLASHING

Counterflashing, generally made of sheet metal, is a removable and reusable component that allows for reroofing without demolishing other components of the detail. Galvanized steel is most commonly used for counterflashing, but aluminum, copper, or stainless steel is specified for greater durability. Counterflashing laps over the top of membrane flashing to prevent the entry of water between the membrane flashing and the parapet wall.

PARAPET COPING

The coping on the top of a parapet wall is generally made of sheet metal. The coping wraps over a continuous metal cleat on the outside face of the parapet and is fastened to the parapet nailer with high-domed, neoprene-gasketed fasteners on the inside face of the parapet.

In place of the metal copings fabricated in the contractor's shop (shown in Figures 33.28 and 33.29), manufacturer-fabricated sheet-metal copings may be specified. Most manufacturers' copings are spring loaded so that they can be snapped to continuous cleats on both sides of the coping, precluding the need for external fasteners.

33.10 CURB AND FLANGE FLASHING DETAILS

Curb flashing occurs at a curb placed at a building expansion joint, around a roof opening such as a skylight, or under rooftop equipment, Figure 33.30. Like base flashing, curb flashing must also extend vertically up the curb, terminating at least 8 in. above the roof level. Figures 33.31 and 33.32 illustrate the principles of curb flashing at an expansion joint.

Flange flashing does not extend vertically but lies in the plane of the roof. It occurs at a free edge of the roof, such as at an edge guard, around a roof drain or vent stack, or around a pipe used for supporting a structural frame under rooftop equipment. Figure 33.33 illustrates a typical edge-guard fascia detail, and Figure 33.34 shows flashing around a pipe penetration.

33.11 PROTECTED MEMBRANE ROOF

In a protected membrane roof (PMR), the insulation is laid loose over the roof membrane, which is generally installed straight on the deck, Figure 33.35. In the case of a steel deck, a leveling board (typically a low-insulation board) is used under the membrane to provide a

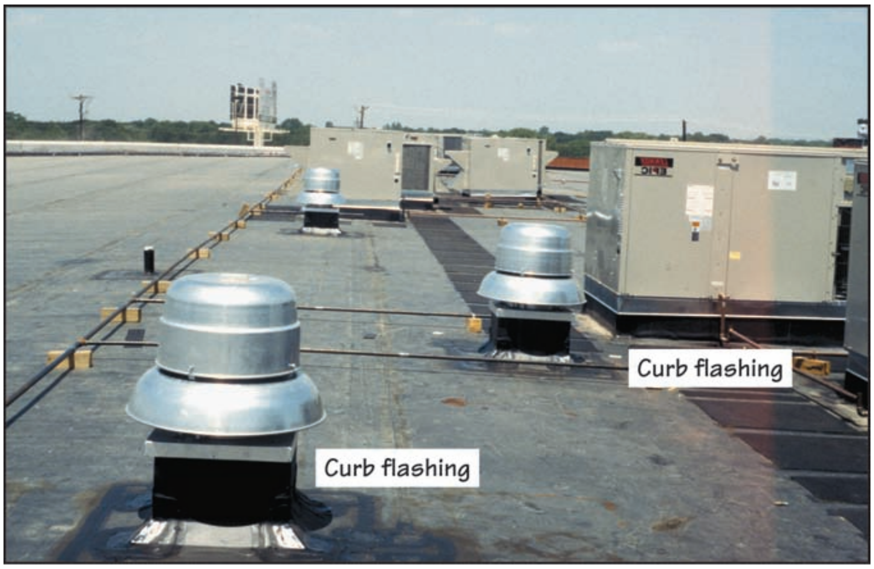


FIGURE 33.30 Examples of curb flashing.

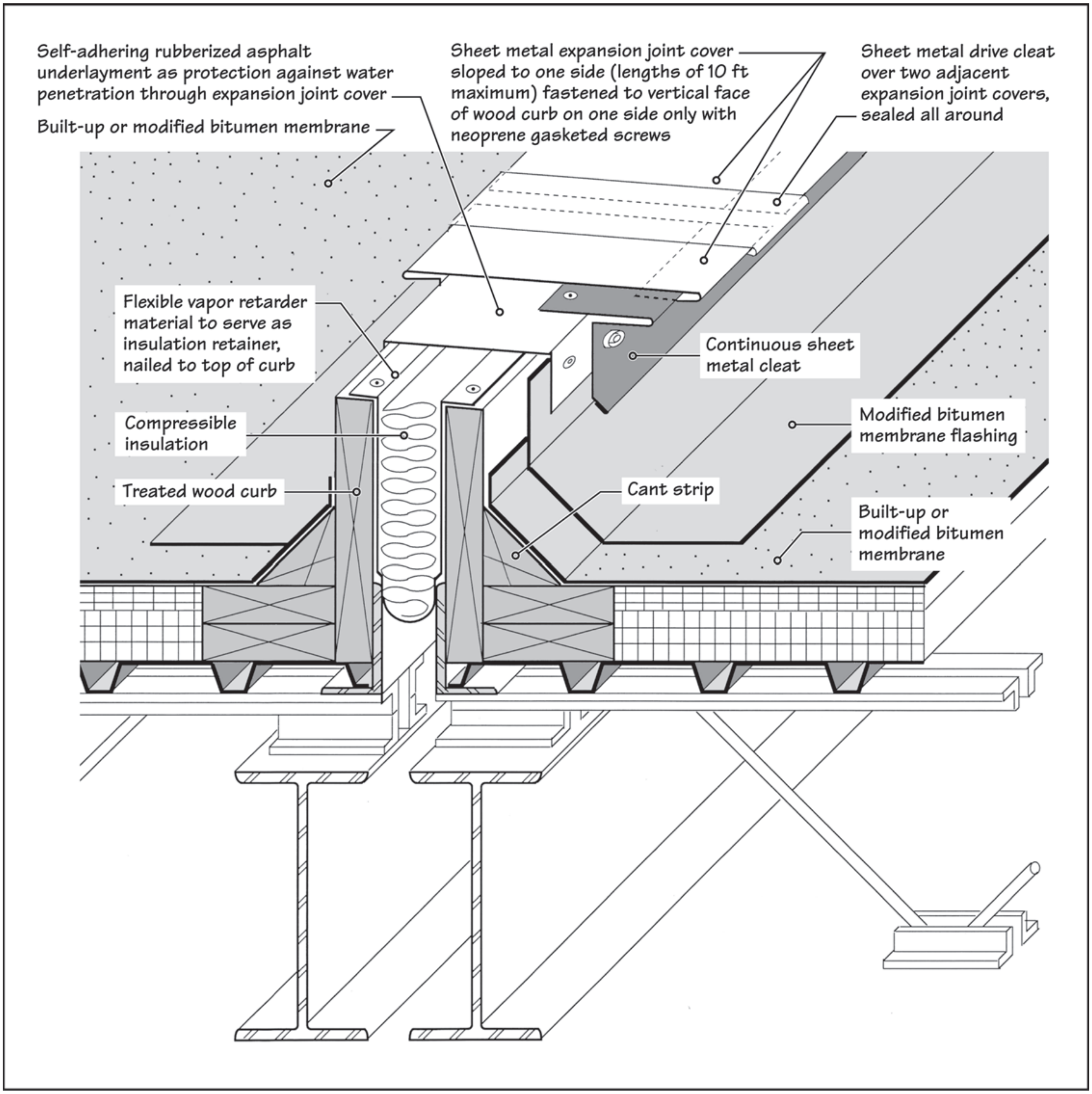

Self-adhering rubberized asphalt underlayment as protection against water penetration through expansion joint cover
Built-up or modified bitumen membrane
Sheet metal expansion joint cover sloped to one side (lengths of 10 ft maximum) fastened to vertical face of wood curb on one side only with neoprene gasketed screws
Sheet metal drive cleat over two adjacent expansion joint covers, sealed all around
Flexible vapor retarder material to serve as insulation retainer, nailed to top of curb
Continuous sheet metal cleat
Compressible insulation
Modified bitumen membrane flashing
Treated wood curb
Cant strip
Built-up or modified bitumen membrane

FIGURE 33.31 A typical roof expansion joint detail with a site-fabricated sheet metal expansion joint cover.

flat, rigid surface. The type of membrane and its installation are similar to those in a conventional roof assembly. Any one of the various membranes (built-up roof, modified bitumen, or single-ply membrane) can be used in a protected membrane roof.

After the installation of the membrane and the associated flashings at the roof perimeter and penetrations, the membrane is covered with insulation, which is then covered with ballast. The ballast may consist of river gravel or precast-concrete pavers. Pavers make the entire roof surface walkable, in addition to providing an easily maintainable roof. Pavers also make the roof look cleaner compared to gravel or crushed stone. Because the order of insulation and roof membrane is reversed in a PMR, it is also referred to as an *inverted roof*.

With the protection provided to it by the insulation and the ballast cover, the roof membrane is shielded from weathering elements, such as ultraviolet radiation and hail and traffic impact. The membrane is also protected from thermal cycling—a major cause of a roof membrane's deterioration in a conventional roof assembly where the membrane is the uppermost layer.

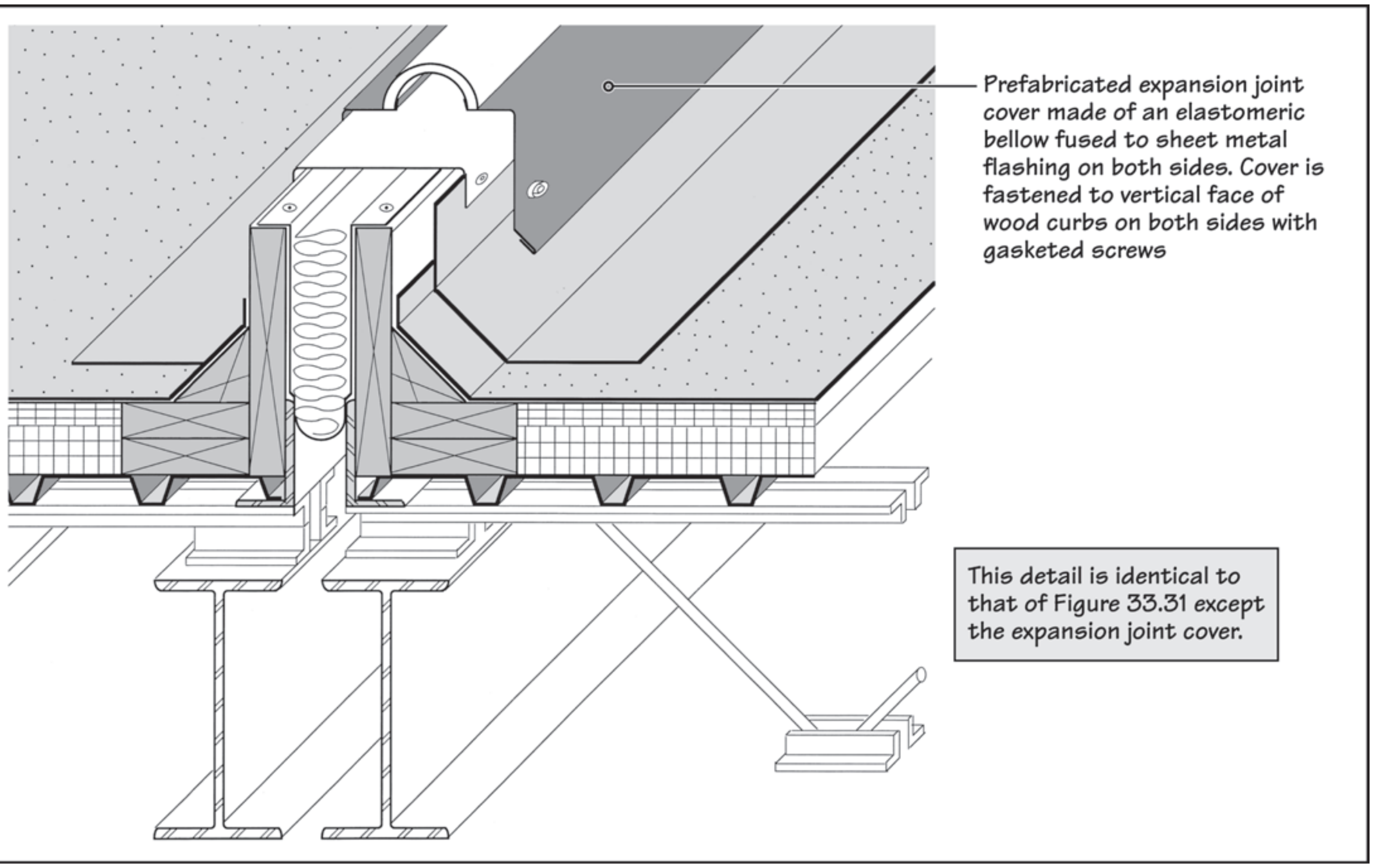

Prefabricated expansion joint cover made of an elastomeric bellow fused to sheet metal flashing on both sides. Cover is fastened to vertical face of wood curbs on both sides with gasketed screws
This detail is identical to that of Figure 33.31 except the expansion joint cover.

FIGURE 33.32 A typical roof expansion joint detail with a prefabricated expansion joint cover.

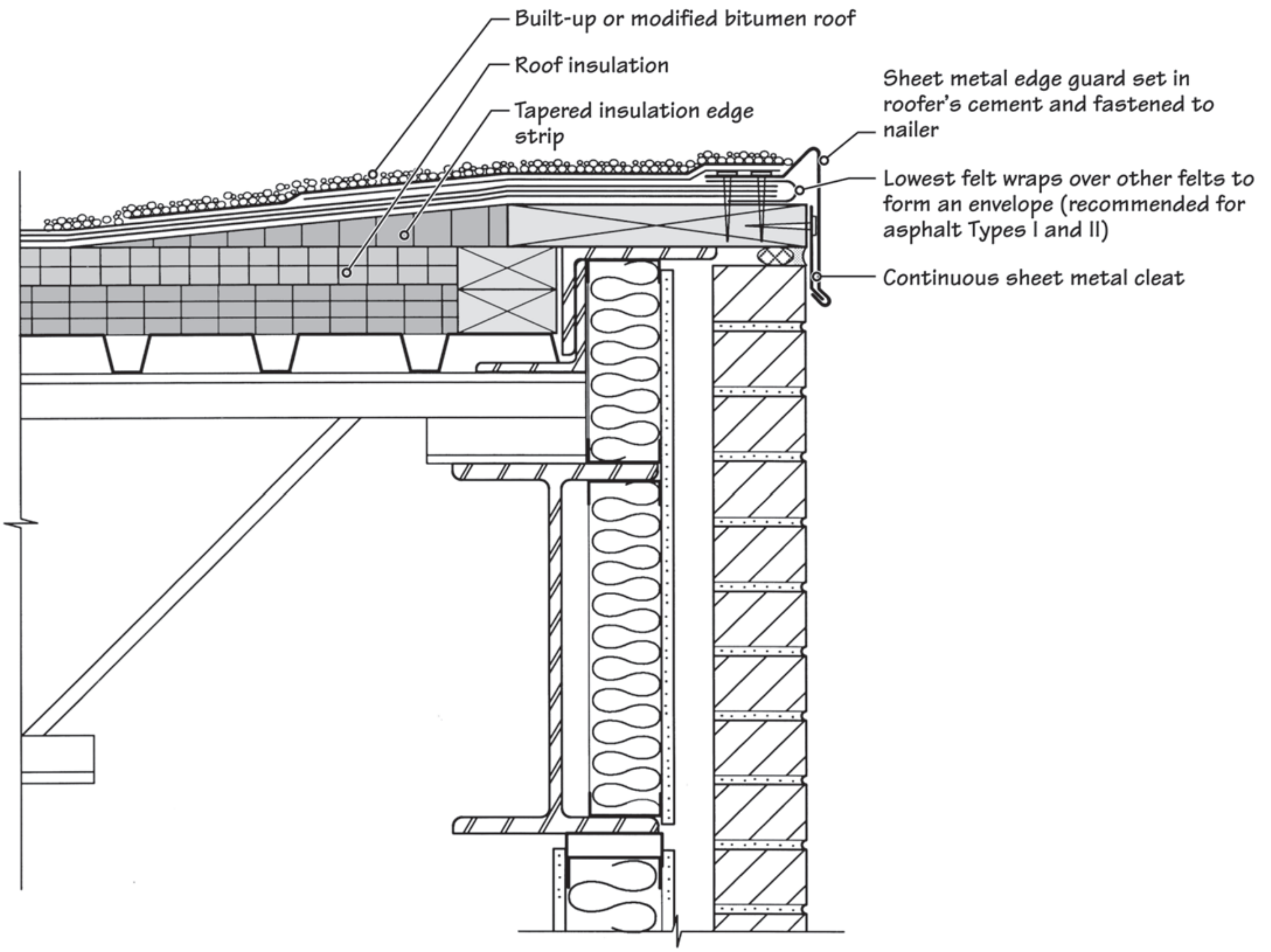

Built-up or modified bitumen roof
Roof insulation
Tapered insulation edge strip
Sheet metal edge guard set in roofer's cement and fastened to nailer
Lowest felt wraps over other felts to form an envelope (recommended for asphalt Types I and II)
Continuous sheet metal cleat

FIGURE 33.33 Flange flashing at an edge guard. This detail shows the use of a built-up roof membrane. Detail using a single-ply membrane is similar.

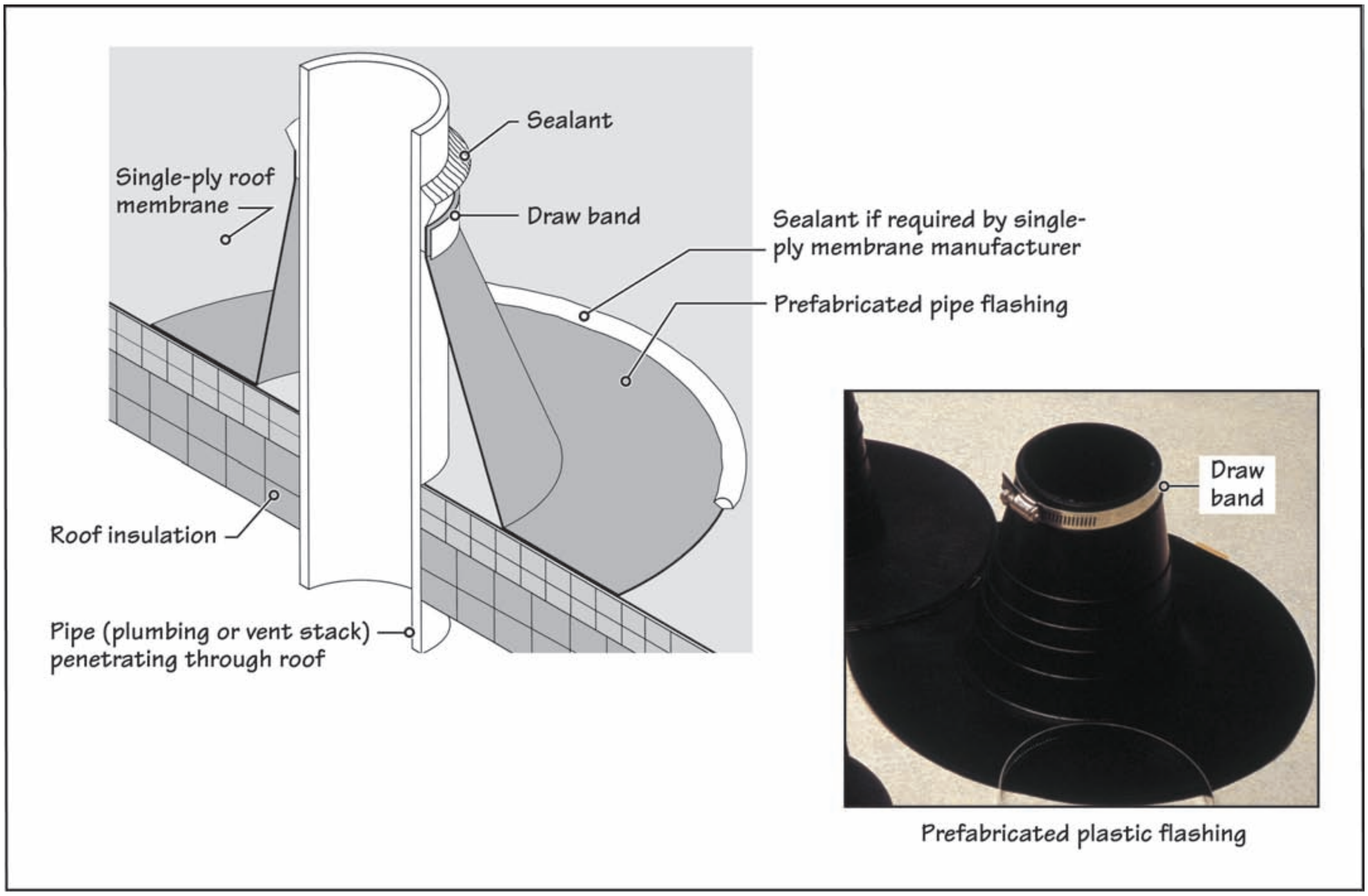

Sealant
Single-ply roof membrane
Draw band
Sealant if required by single-ply membrane manufacturer
Prefabricated pipe flashing
Roof insulation
Pipe (plumbing or vent stack) penetrating through roof
Draw band
Prefabricated plastic flashing

FIGURE 33.34 Flashing around a pipe penetration with a single-ply roof membrane.

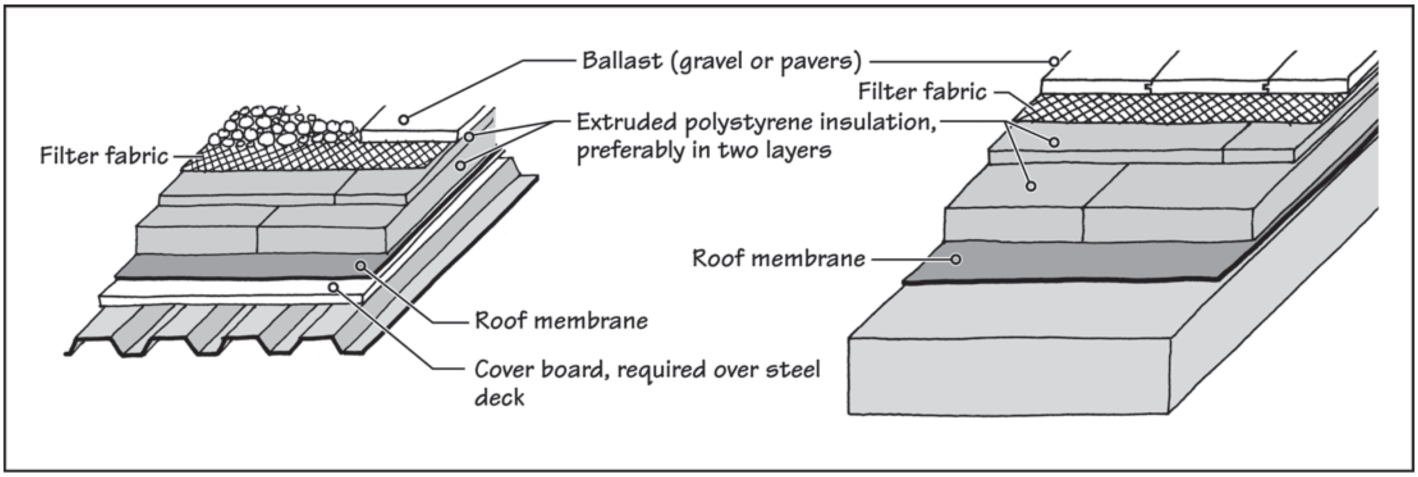

Ballast (gravel or pavers)
Filter fabric
Filter fabric
Extruded polystyrene insulation, preferably in two layers
Roof membrane
Roof membrane
Cover board, required over steel deck

FIGURE 33.35 Components of a protected roof membrane.

INSULATION IN A PROTECTED MEMBRANE ROOF

Because the temperature cycling and weathering elements are borne by the insulation in a PMR, insulation becomes a more critical component of the assembly. PMR insulation must be water impermeable, have high resistance to freeze-thaw cycles, have high compressive strength, and have high dimensional stability. Among the commonly used low-slope roof insulations, extruded polystyrene is the only insulation that meets these and the other requirements of a PMR.

FILTER FABRIC

Another important component in a PMR is a filter fabric, which consists of a porous plastic membrane laid over the insulation. Its purpose is to keep silt and small debris from flowing into insulation joints and restricting the insulation's expansion and contraction. The filter fabric also protects roof drains against blockage by such materials.

33.12 LOW-SLOPE-ROOF DESIGN CONSIDERATIONS

With so many different types of low-slope roofing systems available (membranes, insulation types, and decks), which system is most appropriate for a project? Some of the major factors that affect the selection of an appropriate roof system are as follows:

- *Locally Available Roofing Technology:* In areas where labor is relatively less expensive, built-up and modified bitumen roofs are more common.
- *System's Suitability to the Local Climate:* In extremely cold climates, a mechanically fastened or ballasted single-ply system may be more appropriate than a fully adhered single-ply or hot-asphalt-applied membrane system because both asphalt and single-ply membrane adhesives require additional precautions when applied in a cold environment.
- In a high-wind region, fully adhered systems are more appropriate because the uplift stresses are distributed over the entire roof membrane instead of being concentrated at the fasteners, as in mechanically fastened systems. A ballasted system should be avoided, and a mechanically fastened system should be detailed with care.
- *Curved Roofs and Roofs with Large Slopes:* Such roofs do not lend themselves to the applica tion of hot bitumen. A fully adhered single-ply membrane is generally more appropriate for such projects.
- *Chemical Environment on the Roof:* Roof membranes on industrial facilities and commercial kitchens must be examined to ensure the membrane's compatibility with the environment on the roof. Roofing-system manufacturers generally provide the required information.
- *Roof Warranty:* Everything else being the same, the manufacturer's warranty may impact the system's selection.
- *Long-Term Cost and Sustainability Aspects of the System:* Although the initial cost of the system is important, its long-term life-cycle cost should not be overlooked. The effect of the system on the environment during and after the roof installation should also be considered.

LIFE-SAFETY ISSUES IN LOW-SLOPE ROOF DESIGN

In addition to the factors just mentioned, the following three life-safety issues impact a roof system's selection:

- Fire-safety considerations
- Wind-uplift and hail-impact resistance
- Drainage design

FIRE SAFETY

Roof systems are separated into three classes in order of decreasing fire safety. Data obtained from the tests conducted by the Underwriters Laboratory (UL) on full-sized roof assembly specimens are considered to be most authoritative. UL classification is based on the exposure of a roof to an exterior fire. (The fire-resistance rating of construction assemblies [see Chapter 7] are based on fire assumed to originate from the interior of the building.) The three UL roof classes are as follows:

- Class A roof
- Class B roof
- Class C roof

Class A is the most fire-resistive and Class C is the least fire-resistive roof. Generally, the fire rating of a given roof system decreases with increasing slope because the exterior fire spreads more easily on a roof with a larger slope. Additionally, gravel-covered, ballast-covered, or foil-covered roofs are generally more fire resistive than those without such covers.

WIND-UPLIFT AND HAIL-IMPACT RESISTANCE

A low-slope roof system must be designed to withstand twice the maximum expected design wind uplift on a roof. In other words, if the maximum expected wind uplift on a roof is 75 psf, the roof system must be able to withstand at least 150 psf, which implies a minimum safety factor of 2.0.

The Factory Mutual Research Corporation (FMRC) is the most widely recognized establishment for rating roof assemblies for wind-uplift and hail-impact resistance. FMRC data, obtained from tests conducted on full-sized roof-assembly specimens, are provided in the following format:

Class 1-60 and Class 1-SH

In this classification, 1 implies that the assembly has passed the calorimeter test—a pass-fail test that measures the amount of combustible content in the assembly. An assembly that exceeds the combustible content limit fails the test and is not tested for any other performance (wind or hail). An assembly that passes the calorimeter test is called an *approved assembly*.

Thus, Class 1-60 implies an approved assembly with wind-uplift resistance of 60 psf. Such an assembly can be used on a roof designed to withstand a maximum wind uplift of 30 psf. Similarly, 1-240 means an assembly can be used where the design wind uplift on roof is 120 psf.

Class 1-SH implies an approved assembly that can withstand severe hail impact. In terms of hail resistance, a roof assembly is rated either as 1-SH or 1-MH. A 1-MH rating implies an approved assembly that has medium hail-impact resistance.

Manufacturers of roof systems provide UL and FMRC ratings of their assemblies—important considerations in roof system's selection.

DRAINAGE DESIGN

After the appropriate roof system has been selected, the roof's drainage design is completed. Like fire and wind, drainage design is an important life-safety issue because a poor drainage design can lead to the collapse of a low-slope roof, which is generally an abrupt collapse.

FOCUS ON SUSTAINABILITY

Sustainability Considerations in Low-Slope Roofs

In response to sustainability concerns, manufacturers of roofing systems have introduced a number of ecofriendly initiatives.

Recycling of Roofing Materials and Reuse of Industrial Wastes

Recycling has been initiated throughout the roofing industry. Built-up roofing and modified bitumen roofing products are being recycled for use in asphalt pavements for roads and highways. Prior to this initiative, nearly 9 million tons of asphalt roofing ended up in landfills in the united states.

New roofing products are being developed from waste obtained from old single-ply roofs, automobile tires, shoes, and several other products. The industry is conscious of the need to make recycling and reuse economically viable.

Roof Surface Reflectivity and Global Warming—The Cool Roof Approach

Another effective means of increasing a roof's sustainability is to improve its energy efficiency by increasing the reflectivity of its surface, thus reducing its solar heat absorption. The commonly used black roofs absorb approximately 80% of the solar energy incident on the roof. If the roof surface is white, its solar energy absorption is reduced to about 20%, which can reduce the roof surface temperature by as much as 15°F to 20°F, reducing the peak cooling loads substantially during the summers.

As one might expect, the use of a reflective roof does not significantly increase the heating load in winters for the following reasons:

- On an annual basis, the heat loss through a roof is typically much smaller than the heat gain. For example, when it is 30°F outside and 70°F inside, the temperature differential between the inside and the outside is 40°F. (It may even be less on a sunny day because the roof's surface temperature will be greater than 30°F.) In a warm climate, a dark roof's surface temperature may be 140°F or more, resulting in a temperature differential of 70°F.
- In the wintertime, the Sun is much lower in the sky and solar radiation is less intense. Winter days are also shorter. Therefore, the Sun's heating potential is lower in winter than in summer. (When passive solar heating is used in buildings in cold climates, we generally make use of sunshine through the windows.)
- There are more cloudy days and, in some regions, the roofs may be covered with snow for extended periods during the winter.

The most important advantage of reflective roofs is their contribution to moderating the urban heat island effect and, hence, global warming. LEED 2009 offers one credit when roof membranes with a solar reflectance index (SRI) of 0.78 or greater are used in low-slope roofs. (According to the Cool Roof Rating Council, the SRI of a "standard black" surface is zero and that of a "standard white" surface is 1.0.)

A reflective roof's lower surface temperature also decreases the membrane's degradation, increasing the service life of the roof. Roofing membrane manufacturers are developing and promoting white roofs through white single-ply membranes or membranes coated with reflective surfaces. More and more cities now require the use of white roofs to obtain LEED certification and lower utility bills. White aggregate- or ballast-covered roofs generally do not qualify as white roofs because they lose their reflectivity fairly rapidly.

Landscaped (Green) Roof Approach

Landscaped roofs, also called *green roofs*, containing vegetation planted on a lightweight soil or another growth medium, have received considerable attention. Like cool roofs, landscaped roofs reduce energy consumption in the building and the urban heat island effect. Unlike cool roofs, however, they also absorb air pollution, control stormwater runoff by temporarily storing rainwater on the roof, and provide wildlife habitat. Their higher initial cost (because of the greater roof load, enhanced waterproofing requirements, and larger number of roof system components) and higher maintenance cost are deterrents against their widespread use.

PRINCIPLES IN PRACTICE

Shingling of Built-Up Roof Felts

The recommended application procedure of a built-up roof membrane involves the shingling of felts, Figure 1. Layer-by-layer application (i.e., phased application) of felts is discouraged.

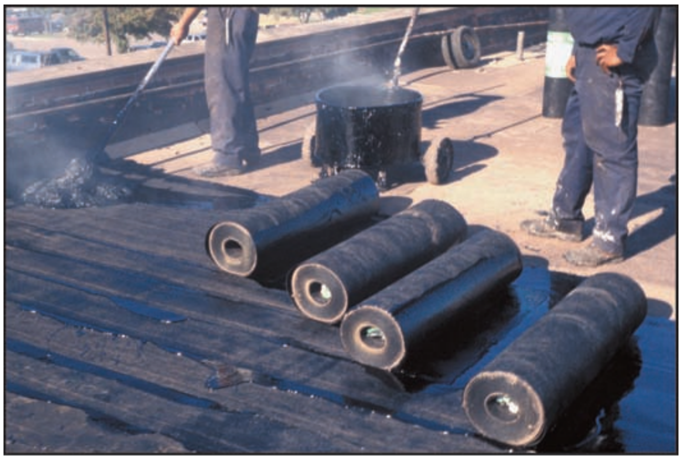


FIGURE 1 Successive built-up roof felts are generally laid in shingle fashion, with the upper felt overlapping the lower felt by a constant dimension. The alternative, applying the felts layer by layer (i.e., in a phased manner), has several disadvantages, and is not used.

In a shingled application, the upper felt overlaps the lower felt by a constant dimension. In a three-ply roof membrane, there are at least three felts under any roof point. Similarly, a four-ply roof must have four felts at every point.

In a shingled built-up roof (BUR), the lap at the exposed end of a felt with respect to the lowest felt under that end, referred to as the *head lap*, is 2 in. as the industry standard. Under the head lap, there is one additional felt. Thus, there are four felts under a head lap in a three-ply membrane, Figure 2. The dimension EXP is called the *exposure* of the felt. EXP is related to the number of plies by the following relationship:

$$\boxed{\text{EXP} = \frac{\text{felt width-head lap}}{\text{number of BUR plies}}}$$

Thus, with a felt width of 36 in., EXP (in a two-ply membrane) $=$ 17 in. In a three-ply membrane, EXP $= 11\frac{1}{3}$ in., and so on. Built-up roof felts are manufactured with two-, three-, and four-ply lines marked on them, as shown in Figure 3, to help roofers lay the felts correctly.

To provide the necessary number of felts at the starting edge of the roof (usually the roof's lowest edge), the first few felts are not the full width of 36 in. The width of the starter felts is obtained simply by dividing the full width by the number of built-up roof plies.

Thus, in a four-ply membrane, there are three partial-width felts at the starting edge—9 in., 18 in., and 27 in. wide, Figure 4. In a three-ply membrane, there are two partial-width felts—12 in. and 24 in. wide. In a two-ply built-up roof membrane (not usually specified), there is only one partial-width felt—18 in. wide.

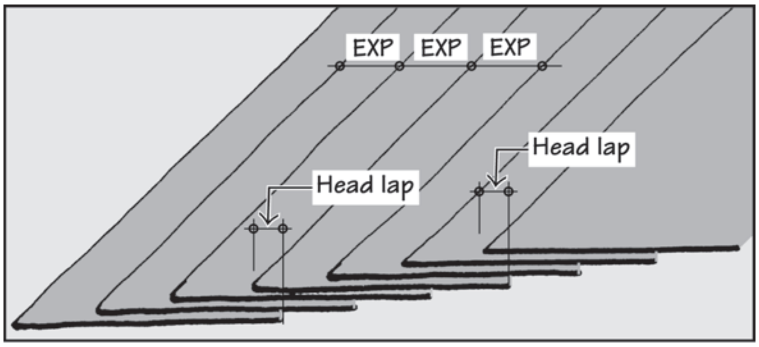


FIGURE 2 Shingling of felts in a built-up roof, with terms exposure (EXP) and head lap indicated. The industry standard for the head lap is 2 in. This sketch shows a three-ply built-up roof membrane.

(*Continued*)

PRINCIPLES IN PRACTICE

Shingling of Built-Up Roof Felts (*Continued*)

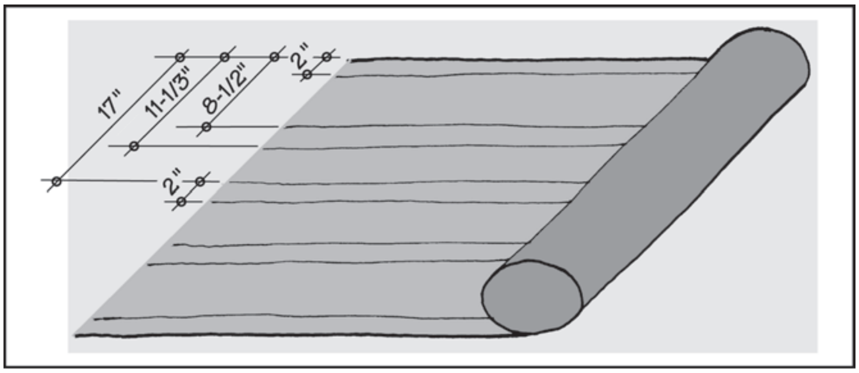


FIGURE 3 Factory-applied lines on a built-up roof felt. The spacings between lines on the left side of the felt are the same as on the right side.

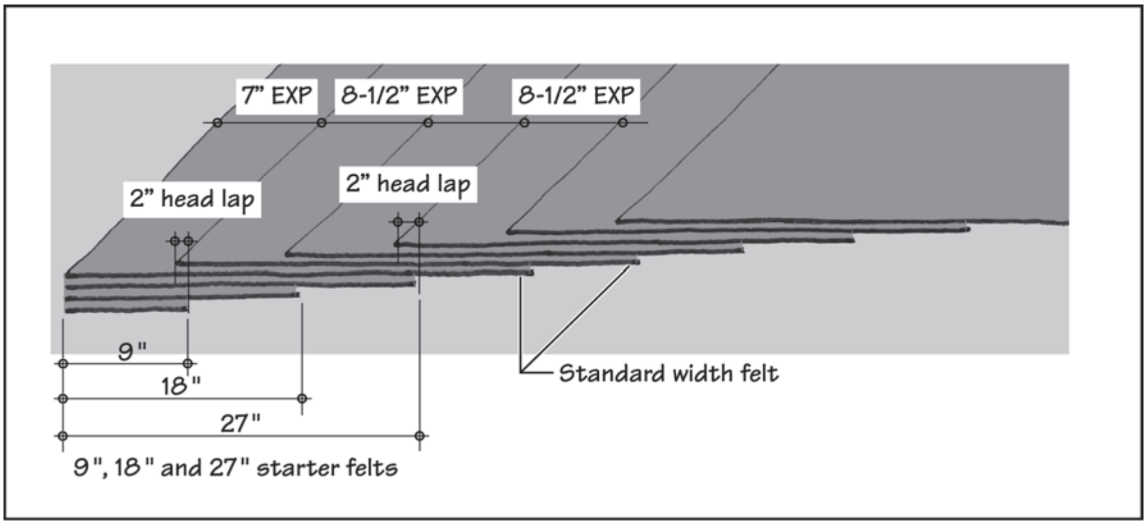


FIGURE 4 The use of starter felts at the starting edge of a built-up roof membrane. This illustration shows a four-ply membrane.

ADVANTAGES OF SHINGLING

Shingling of felts results in completed sections of the roof at the end of each day. Thus, the membrane remains protected from interply moisture penetration during interruptions in roofing operations. If the felts were laid in a phased manner, moisture might be trapped between the felt layers, either from rain or from overnight condensation. The entrapment of debris in a phased application is also of concern.

Another advantage of shingling is that it provides better adhesion of plies compared to the phased application. This is due to the slower cooling of bitumen in a shingled membrane. In a shingled membrane, three to four layers of bitumen are applied within a short time span. In a phased application, the previous layer of bitumen has virtually cooled off when the subsequent layer is applied.

Each question has only one correct answer. Select the choice that best answers the question.

28. The flashing around a pipe penetrating through the roof is
- **a.** base flashing
- **b.** curb flashing.
- **c.** flange flashing.
- **d.** none of the above.

29. The flashing around a roof drain is
- **a.** base flashing
- **b.** curb flashing.
- **c.** flange flashing.
- **d.** none of the above.

30. A cant strip is not required in a base flashing detail with a single-ply roof membrane.
- **a.** True
- **b.** False

31. Counterflashing is generally
- **a.** made of PVC and is permanently anchored to the deck or parapet wall.
- **b.** made of PVC and is a removable item.
- **c.** made of sheet metal and is permanently anchored to the deck or parapet wall.
- **d.** made of sheet metal and is a removable item.
- **e.** none of the above.

32. In a protected membrane roof, the insulation is
- **a.** below the deck.
- **b.** between the deck and the membrane.
- **c.** above the membrane and fully adhered to it.
- **d.** above the membrane but loose laid over it.
- **e.** not used.

33. FM 1-120 represents
- **a.** the fire rating of a roof assembly.
- **b.** the wind-uplift resistance of a roof assembly.
- **c.** the hail-impact resistance of a roof assembly.
- **e.** none of the above.

34. UL Class B represents
- **a.** the fire rating of a roof assembly.
- **b.** the wind-uplift resistance of a roof assembly.
- **c.** the hail-impact resistance of a roof assembly.
- **e.** none of the above.

35. FM MH represents
- **a.** the fire rating of a roof assembly.
- **b.** the wind-uplift resistance of roof assembly.
- **c.** the hail-impact resistance of roof assembly.
- **d.** none of the above.

36. The exposure (EX) of felts in a four-ply built-up roof is
- **a.** 2 in.
- **b.** 4 in.
- **c.** 6 in.
- **d.** 8 in.
- **e.** none of the above.

37. The head lap in a four-ply built-up roof is
- **a.** 2 in.
- **b.** 4 in.
- **c.** 5 in.
- **d.** 6 in.
- **e.** none of the above.

REVIEW QUESTIONS

1. Using a sketch, explain the essential components of a low-slope roof.
2. Discuss the differences between SBS-modified and APP-modified bitumen roof membranes.
3. Explain the differences between an inorganic (fiberglass) roofing felt and an organic roofing felt.
4. Explain the differences between coal tar and asphalt as roofing bitumen, and state why coal tar is not commonly used.
5. What is the difference between the terms *felt* and *ply?* List various asphalt-treated fiberglass roofing felts and briefly explain the differences between them.
6. What is the size of a typical built-up roof felt, and what is its relationship with a roof square?
7. Explain the difference between thermosetting and thermoplastic roof membranes, and give at least one example of each. How does the difference between the two types influence the sealing of lap seams between adjacent membranes?
8. What is a roof cover board and what material is it made of? Explain.
9. What are the functions of a roof cover board? Explain.
10. Using sketches, explain the anatomies of the following roofs. Show how the insulation and roof membrane are attached.
    - a. Steel deck, rigid board insulation, and built-up roof membrane
    - b. Reinforced-concrete deck, rigid board insulation, and SBS-modified bitumen membrane
    - c. Steel deck, foamed-concrete insulation, and built-up roof membrane
    - d. Concrete deck, rigid board insulation, and loose-laid, ballasted single-ply membrane
11. Explain what a cool roof is, and state its advantages and limitations.
12. List and briefly explain the life-safety issues in roofing design.
13. With the help of a sketch, describe a protected membrane roof.

CHAPTER 34

Roofing-II (Steep Roofs)

CHAPTER OUTLINE

34.1 Steep-Roof Fundamentals

34.2 Asphalt Shingles and Roof Underlayment

34.3 Installation of Asphalt Shingles

34.4 Valley Treatment in an Asphalt Shingle Roof

34.5 Ridge and Hip Treatment in an Asphalt Shingle Roof

34.6 Flashings in an Asphalt Shingle Roof

34.7 Essentials of Clay and Concrete Roof Tiles

34.8 Clay and Concrete Tile Roof Details

34.9 Types of Sheet-Metal Roofs

34.10 Contemporary Architectural Metal Roofs

As a continuation of the previous chapter, in which low-slope roofs were discussed, this chapter deals with steep roofs—roofs that have a slope of greater than or equal to 3:12. It begins with an introduction to the components of a steep roof and then discusses the types of steep roofs commonly used. Of the various types of steep roofs, asphalt shingle roofs are most commonly used. Therefore, asphalt shingle roofs are covered in greater detail than the other roof types.

As mentioned in Chapter 33, a roof type that is used for both low-slope and steep roofs is the architectural sheet-metal roof. Architectural sheet-metal roofs are becoming increasingly popular because of their greater durability and the availability of a vast array of nonfading colors. Architectural sheet-metal roofs are covered at the end of the chapter.

34.1 STEEP-ROOF FUNDAMENTALS

The basic components of a steep roof are illustrated in Figure 34.1:

- Roof shingles
- Roof underlayment
- Ice dam protection membrane, where needed
- Roof deck
- Flashings

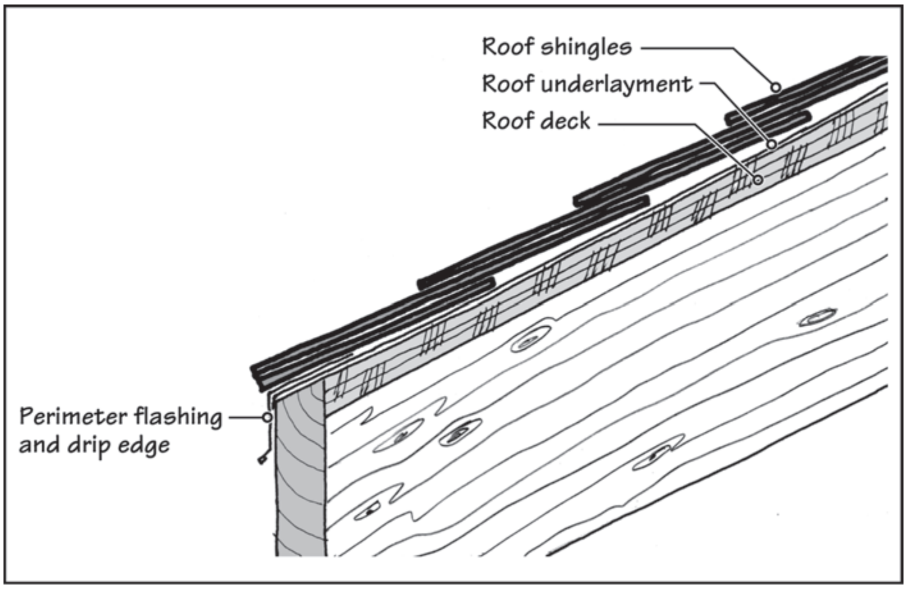


FIGURE 34.1 Components of a steep roof. (Insulation in the attic under a steep roof and the attic's ventilation may also be considered as components of a steep roof; see Chapter 5 and Section 6.8.)

ROOF SHINGLES

Roof shingles can be of various types. The more commonly used shingle varieties are:

- Asphalt shingles
- Slate shingles
- Concrete and clay tiles
- Wood shingles
- Metal shingles

As stated earlier, asphalt shingles (also called *composition shingles*) have the largest steep-roof market share because of their low cost and acceptable life span. They are available in different colors and textures and have aesthetic appeal. With shadow lines added to their surface, some varieties can mimic a wood shingle roof. Another advantage of asphalt shingles is their light weight, which reduces labor and transportation costs and also the cost of the structural components of the roof.

Slate shingles have one of the longest recorded histories of use. They have been used in many buildings of historic importance in Europe and the United States. Because slate is a hard, dense natural stone, slate roofs last a long time. They perform quite well when subjected to repetitive freeze-thaw cycles. Well constructed and detailed, slate roofs can last for 75 years or more. Obviously, they are expensive. Imitation slates are also available, but their performance records must be checked before specifying them.

Clay tiles create a handsome roof due to the availability of a large variety of tile shapes. Like slate roofs, clay tile roofs are quite durable. However, it is important to understand that there can be significant differences in the quality of tiles, which can affect the durability of a clay tile roof.

Concrete tile roofs, though fairly durable, are generally less so than clay tile roofs. There can also be problems with long-term fading of colors of concrete tiles.

Wood shingles and shakes, once extensively used in the United States, have a decreasing market share today because of their fire hazard. Although fire-retardant-treated wood shingles are available, their long-term performance history is uncertain. A large variety of metal shingles are used in contemporary steep roofs. Like wood shingles, their market share is also small.

ROOF UNDERLAYMENT

In a properly designed and constructed steep roof, rainwater should normally not get under the shingles. However, a water-resistant layer, called a *roof underlayment*, is required under the shingles throughout the roof as a second line of protection against water leakage. The requirements for the type of roof underlayment varies with the type of shingles and the roof slope. (Wood shingles do not require underlayment in some situations.)

A valley requires an additional roofing layer, referred to as a *valley underlayment*. A valley is more vulnerable to water leakage than the field of the roof because its slope is smaller than that of the roof itself. For example, the slope of a valley created by two intersecting planes, each with a slope of 4:12, is only 2.8:12—a 30% reduction in slope, Figure 34.2.

A significant head of water can be present in a long, flat valley. In addition to a smaller slope, the water running through the valley experiences more turbulence because it arrives there from two opposite directions.

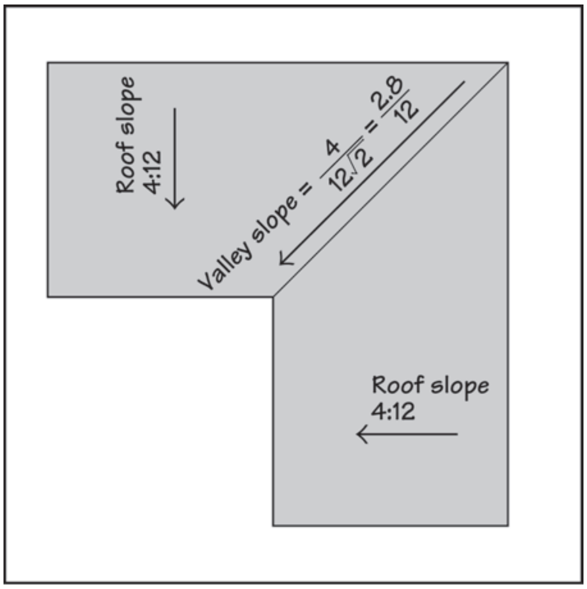


FIGURE 34.2 The roof slope in a valley is much lower than that in the rest of the roof. Therefore, a valley requires additional (valley) underlayment; see Figure 34.14.

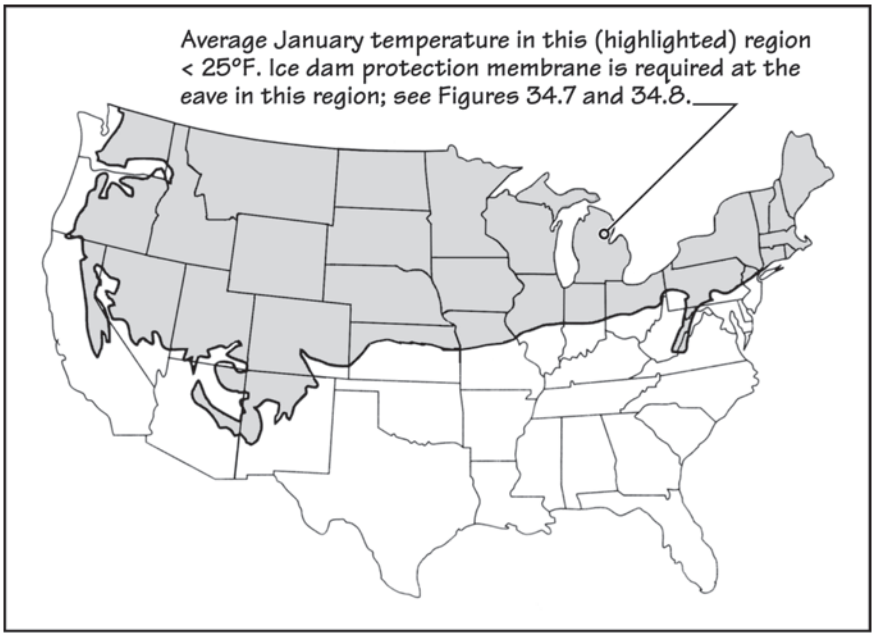

Average January temperature in this (highlighted) region < 25°F. Ice dam protection membrane is required at the eave in this region; see Figures 34.7 and 34.8.

FIGURE 34.3 Approximate areas of the United States where the use of an ice dam protection membrane at the eave is recommended. The local building code should be consulted for precise information.

ICE DAM PROTECTION MEMBRANE

Another special type of underlayment is called an *ice dam protection membrane*. It is required for use at the eaves in climates where there is a potential for the formation of ice at an overhanging eave.

The formation of an ice dam can make water back up under the shingles (see Figure 6.11). Ice dam protection is recommended in regions where the average daily temperature in January is less than 25°F, Figure 34.3. However, many roofers and roofing consultants recommend the provision of an ice dam protection membrane at the eaves in all locations.

ROOF DECK

The deck, being a structural component of the roof, is its most important element. In a contemporary steep roof, the deck generally consists of plywood or oriented strandboard panels. A spaced deck, consisting of wood lath (typically 1 × 4 or 1 × 6 wood members spaced according to the length of the shingles), may be used with some steep-roof types, but its use is limited today.

FLASHINGS

As in low-slope roofs, flashings are additional waterproofing components used to create a watertight seal at terminations and transitions in the roof. Critical areas for flashings are valleys, eaves, rakes, chimneys, and other penetrations.

Flashings around roof penetrations, such as a chimney or a pipe, are particularly critical. The water is not only interrupted by a penetration but redirected and compressed on a smaller area of the roof as it flows around a penetration.

34.2 ASPHALT SHINGLES AND ROOF UNDERLAYMENT

Asphalt shingles are manufactured in strips measuring approximately 36 in. × 12 in., with up to five cutouts. The cutouts separate a shingle strip into tabs, making the strip appear to be composed of several smaller shingles, which improves the shingle's appearance.

Asphalt shingles vary in weight from about 200 lb to nearly 400 lb per roof square. The heavier varieties, which consist of two or more layers of shingles laminated together, are generally more durable and aesthetically more pleasing.

Each shingle strip is made from a fiberglass mat, which is saturated and coated with asphalt and surfaced with mineral granules. The granules give the desired surface color to a shingle, which may vary from white, gray, and black to various shades of red, brown, and green, Figure 34.4.

Three of the most commonly used asphalt shingle profiles are shown in Figure 34.5. Each shingle is coated with a line of self-sealing adhesive, which helps to adhere that shingle with

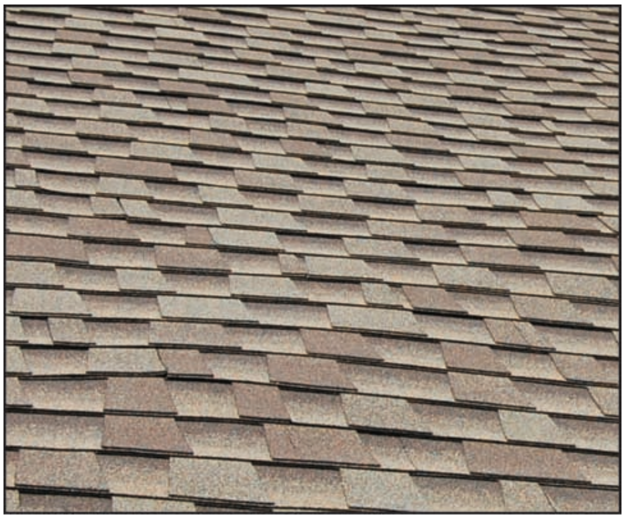


FIGURE 34.4 Asphalt shingles with color variations in their granule surface that give shadow lines to mimic wood or slate roofing.

the overlying shingle. The adhesion is activated by the Sun's heat after the shingles have been installed on the roof. The adhesive line increases the wind resistance of shingles. Of the three self-sealing shingle varieties shown in Figure 34.5, the three-tab shingle is the most commonly specified.

Roof Underlayment and Ice Dam Protection for a Standard-Slope Asphalt Shingle Roof

The recommended roof slope for asphalt shingles is between 4:12 and 21:12. This is referred to as the *standard slope* for asphalt shingles. A slope lower than the standard slope may also be used, but it requires special treatment, Figure 34.6.

The recommended roof underlayment for a standard-slope roof is No. 15 or heavier asphalt-treated organic felt. The underlayment is applied with 2-in. laps at the edges of the roll and 6-in. laps at the ends of the roll, Figure 34.7. It is nominally nailed or stapled to the deck—enough to hold it in place until the shingles are installed. It is essential that the underlayment is turned up the abutting walls or curbs (see Figures 34.22 and 34.24).

The ice dam protection membrane on a standard-slope roof is typically a proprietary product, which is generally a self-adhering (peel-and-stick) modified bitumen sheet. It should extend a distance of at least 24 in. from the exterior wall toward the interior of the building.

NOTE

Asphalt-Treated Organic Felts as Underlayment

As stated in Chapter 33, asphalt-treated organic felts are used as steep-roof underlayment. They are available in two types:

1. No. 15 felt
2. No. 30 felt

When first developed, No. 15 felt weighed 15 lb per roof square and No. 30 felt weighed 30 lb per roof square. Currently, as per the ASTM D226 Standard, No. 15 felt and No. 30 felt weigh 11.5 lb and 26 lb per roof square, respectively.

Because of its greater thickness and weight, a No. 30 felt is more durable and performs better than a No. 15 felt.

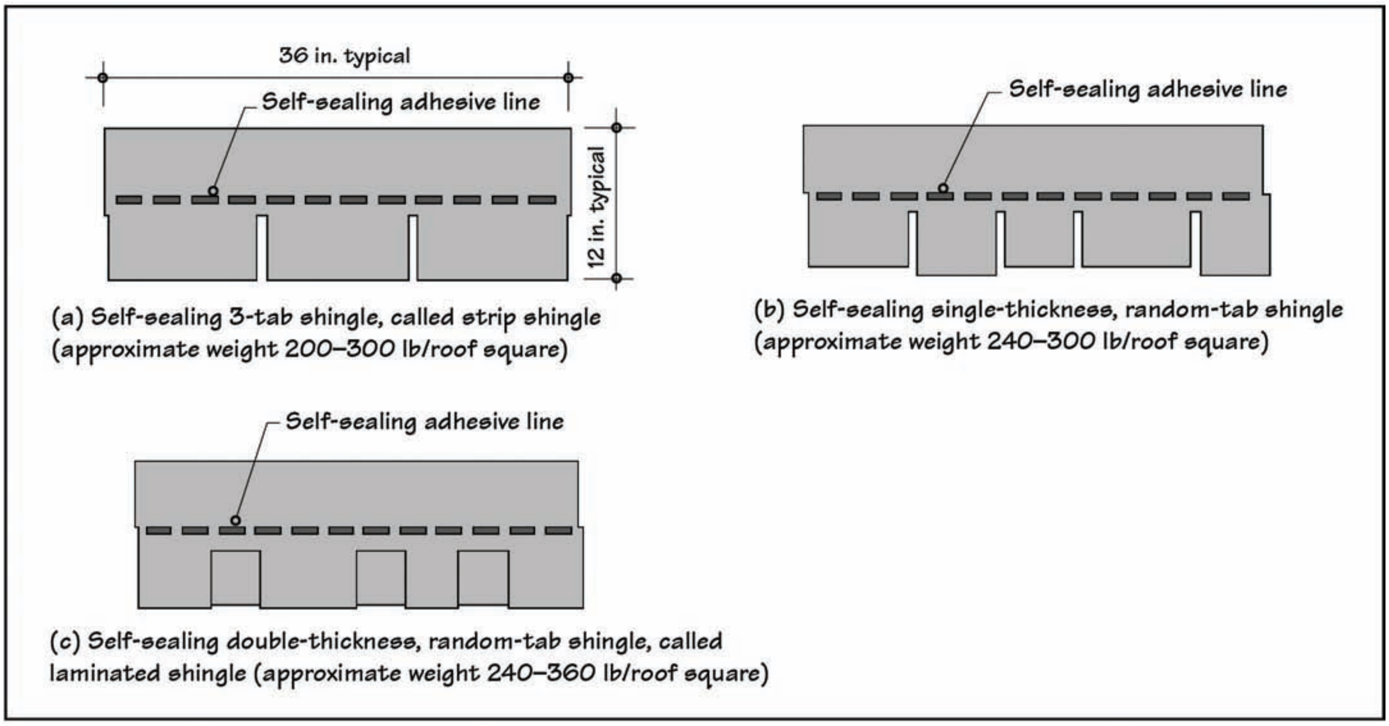

36 in. typical
Self-sealing adhesive line
12 in. typical
(a) Self-sealing 3-tab shingle, called strip shingle (approximate weight 200–300 lb/roof square)
Self-sealing adhesive line
(b) Self-sealing single-thickness, random-tab shingle (approximate weight 240–300 lb/roof square)
Self-sealing adhesive line
(c) Self-sealing double-thickness, random-tab shingle, called laminated shingle (approximate weight 240–360 lb/roof square)

FIGURE 34.5 Commonly used asphalt shingle profiles.

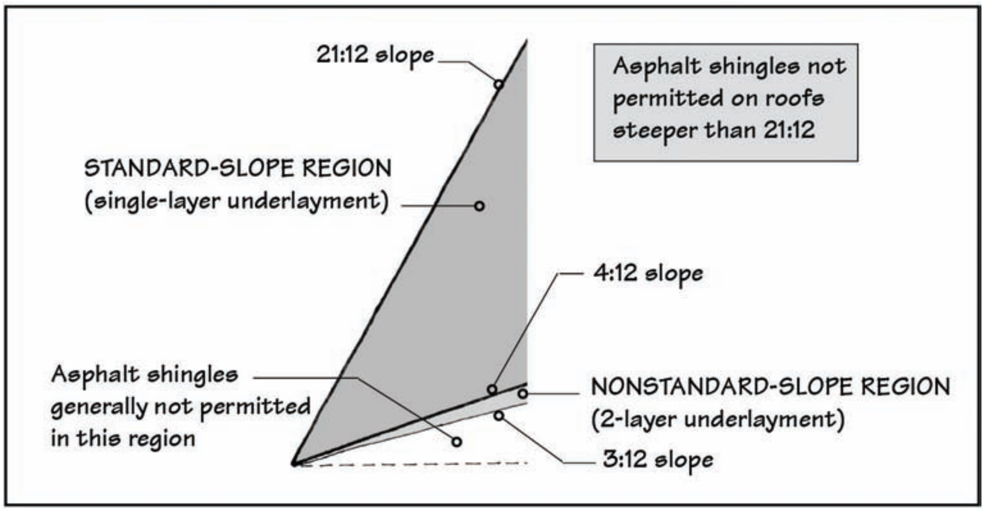

21:12 slope
Asphalt shingles not permitted on roofs steeper than 21:12
STANDARD-SLOPE REGION (single-layer underlayment)
4:12 slope
Asphalt shingles generally not permitted in this region
NONSTANDARD-SLOPE REGION (2-layer underlayment)
3:12 slope

FIGURE 34.6 Slope and underlayment requirements for asphalt shingle roofs.

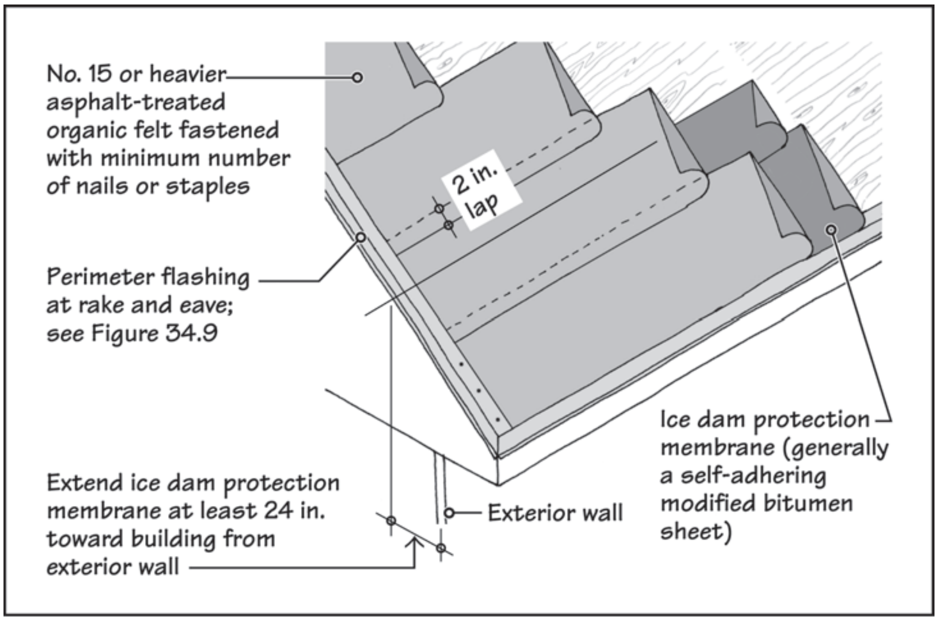

No. 15 or heavier asphalt-treated organic felt fastened with minimum number of nails or staples
2 in. lap
Perimeter flashing at rake and eave; see Figure 34.9
Ice dam protection membrane (generally a self-adhering modified bitumen sheet)
Exterior wall
Extend ice dam protection membrane at least 24 in. toward building from exterior wall

FIGURE 34.7 Roof underlayment and ice dam protection membrane on a standard-slope (≥4:12) asphalt shingle roof.

ROOF UNDERLAYMENT AND ICE DAM PROTECTION FOR A NONSTANDARD-SLOPE ASPHALT SHINGLE ROOF

Asphalt shingles may be used on a roof slope between 3:12 and 4:12, but generally the roof's performance is not as good as that on a standard slope. Note, however, that some asphalt shingle manufacturers permit the use of their product on a slope as low as 2:12. The underlayment on a nonstandard-slope (or low-slope) roof must be a two-layer felt underlayment applied in shingle fashion, Figure 34.8. The ice dam protection membrane should extend a distance of at least 36 in. from the exterior wall toward the interior of the building.

PERIMETER FLASHING AT EAVES AND RAKES—THE DRIP EDGE

A sheet-metal drip edge should be provided at all eaves and rakes and mechanically fastened to the deck. Galvanized steel or prefinished metal is the most commonly used metal for a drip edge, but stainless steel, copper, or aluminum may also be used for higher durability. On an eave, the drip edge is applied before the underlayment is laid. On a rake, on the other hand, it is applied over the underlayment, Figure 34.9.

34.3 INSTALLATION OF ASPHALT SHINGLES

After the roof underlayment and ice dam protection membrane have been installed, the roof is ready to receive the shingles. The procedures used to install various types of asphalt

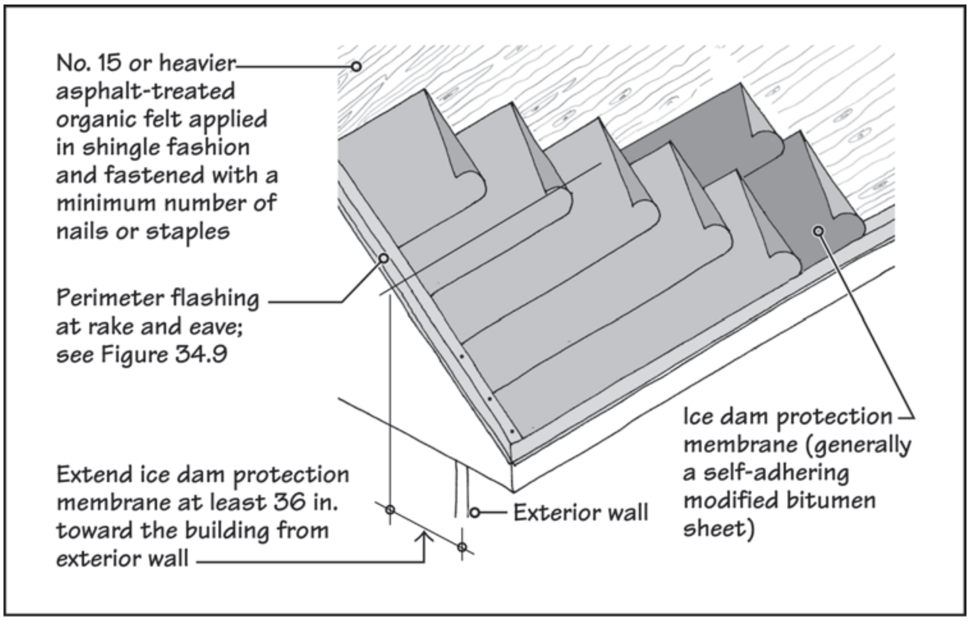

No. 15 or heavier asphalt-treated organic felt applied in shingle fashion and fastened with a minimum number of nails or staples
Perimeter flashing at rake and eave; see Figure 34.9
Extend ice dam protection membrane at least 36 in. toward the building from exterior wall
Exterior wall
Ice dam protection membrane (generally a self-adhering modified bitumen sheet)

FIGURE 34.8 Roof underlayment and ice dam protection membrane on a nonstandard-slope asphalt shingle roof (slope between 3:12 and 4:12).

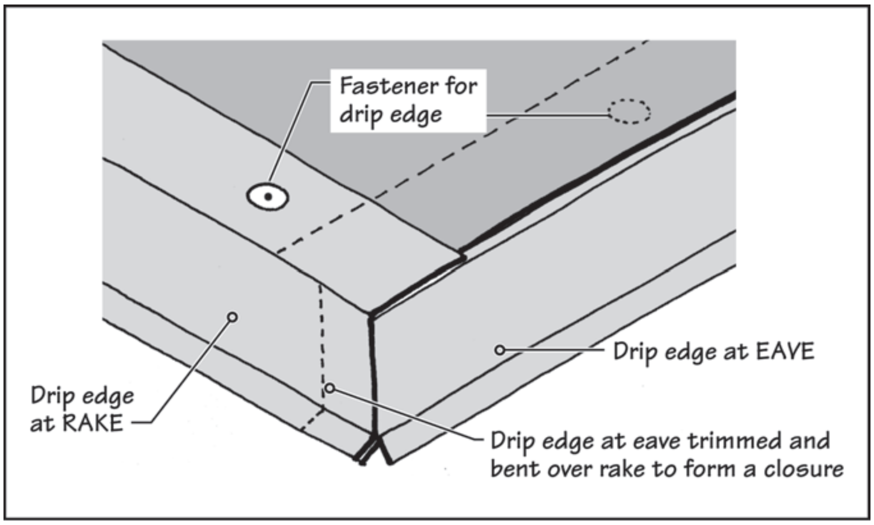

Fastener for drip edge
Drip edge at EAVE
Drip edge at RAKE
Drip edge at eave trimmed and bent over rake to form a closure

FIGURE 34.9 Drip edge at the eave and rake of an asphalt shingle roof.

shingles (see Figure 34.5) is almost identical. Because three-tab shingles are most commonly used, the installation procedure described here refers to their installation.

The installation of three-tab shingles begins with the starter course at the eave, which is applied directly over the underlayment. A starter course consists of the standard three-tab shingles, whose tabs have been cut off, Figure 34.10(a). The remaining part of each shingle, which is nearly 7 in. wide, is nailed to the deck, with the self-sealing adhesive line placed along the outside edge of the eave, Figure 34.10(b).

The self-sealing adhesive line of the starter course bonds with the overlying shingles (of the first course), improving the wind-resistance performance of the roof. The starter course is laid from one end of the roof to the other. The first shingle in the starter course is cut by 3 in. along the shingle's length, so that the joints in the starter course are offset from the joints in the first course of shingles.

Next, the first course of shingles is laid. The first course of shingles fully covers the starter course, and each shingle is a full-length shingle. The second course of shingles is laid so that only the tabs of the first course are exposed, and so on. In other words, asphalt shingles have a double coverage—a two-shingle thickness under every point, except under a headlap, where there is a three-shingle thickness.

The first shingle of the second course is cut in length by $\frac{1}{2}$ tab (nearly 6 in.). This cut breaks the joints in the upper and lower courses of shingles, Figure 34.11. The first shingle of the third course is cut by 1 full tab, nearly 12 in. The first shingle of the fourth course is

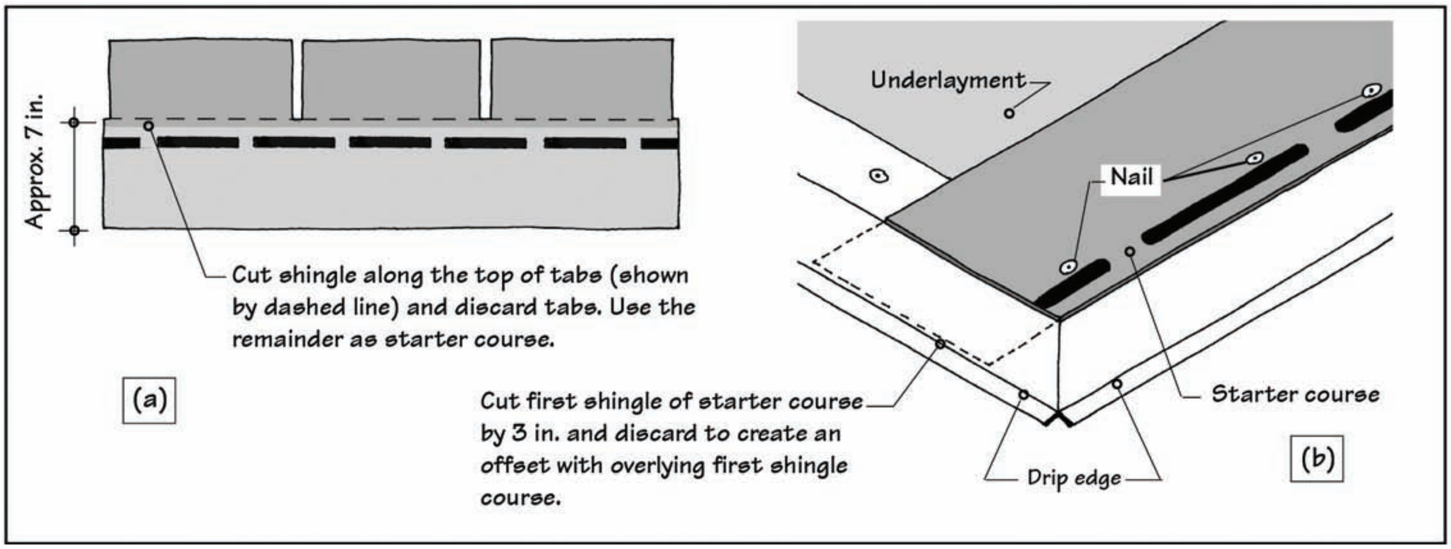

Approx. 7 in.
Cut shingle along the top of tabs (shown by dashed line) and discard tabs. Use the remainder as starter course.
(a)
Underlayment
Nail
Cut first shingle of starter course by 3 in. and discard to create an offset with overlying first shingle course.
Starter course
Drip edge
(b)

FIGURE 34.10 Installation of a starter course in an asphalt shingle roof.

cut by $1\frac{1}{2}$ tabs, and so on. The pattern of shingles generated by this half-tab offset procedure is referred to as the *6-in. offset method*, because the shingles are offset by $\frac{1}{2}$ tab (6 in.). In addition to the 6-in. offset method, the *3-in. offset method, 4-in. offset method*, and *5-in. offset method* are also used.

To improve the performance of the roof, it is desirable to include a course of bleeder strips at the rake, Figure 34.12. A bleeder strip is similar to the starter course.

FASTENERS FOR SHINGLES

Asphalt shingles are fastened to the deck with 11- or 12-gauge galvanized steel roofing nails with $\frac{3}{8}$-in.- to $\frac{7}{16}$-in.-diameter nail heads (see Figure 14.34). Each shingle strip requires a minimum of four nails, placed as shown in Figure 34.13. In high-wind regions and on steep slopes, a greater number of nails may be needed.

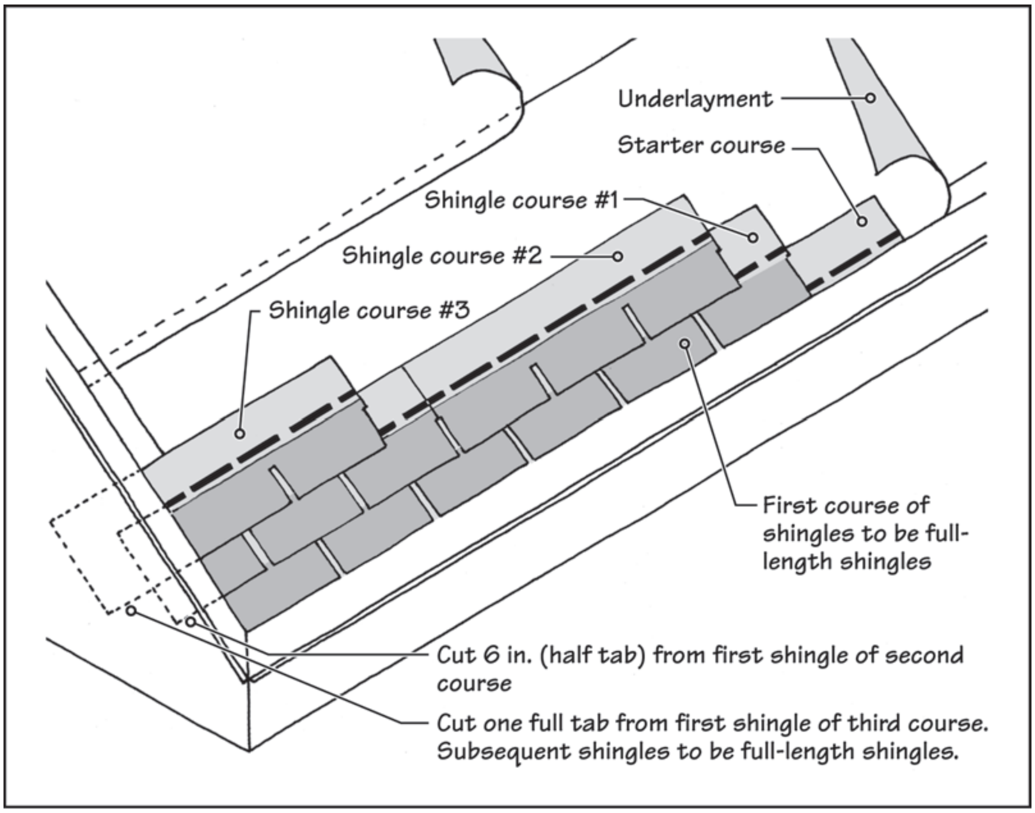

Underlayment
Starter course
Shingle course #1
Shingle course #2
Shingle course #3
First course of shingles to be full-length shingles
Cut 6 in. (half tab) from first shingle of second course
Cut one full tab from first shingle of third course. Subsequent shingles to be full-length shingles.

FIGURE 34.11 Layout of the starter course and the first few shingle courses. Note that asphalt shingles are laid with double coverage—two-shingle thickness under every point except under a headlap, where there is three-shingle thickness.

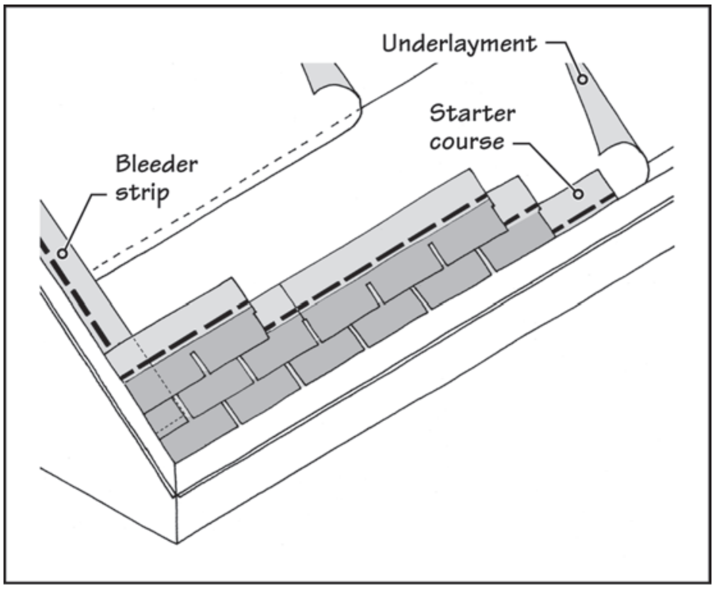


FIGURE 34.12 The use of a bleeder strip at the rake. A bleeder strip shingle is identical to the starter strip shingle at the eave.

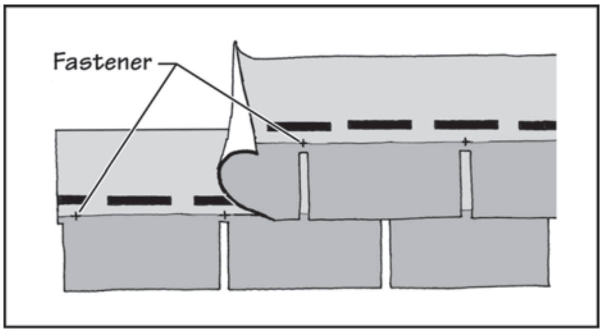


FIGURE 34.13 The standard fastening pattern requires four nails per shingle—one fastener at each end (nearly 1 in. from the end) and one nail between each tab. In high-wind regions, a larger number of nails are needed.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. Which of the following steep-roof materials has the longest history of use?
- **a.** Asphalt shingle
- **b.** Clay tile
- **c.** Concrete tile
- **d.** Slate roofs
- **e.** Wood shingle

2. Which of the following steep-roof materials is most commonly used in contemporary buildings?
- **a.** Asphalt shingle
- **b.** Clay tile
- **c.** Concrete tile
- **d.** Slate
- **e.** Wood shingle

3. In a steep roof, the ice dam protection membrane is generally provided at the
- **a.** ridge.
- **b.** eave.
- **c.** rake.
- **d.** valley.
- **e.** hip.

4. A double-layer roof underlayment is required in an asphalt shingle roof if the roof slope is
- **a.** between 3:12 and 4:12.
- **b.** between 3:12 and 5:12.
- **c.** between 3:12 and 6:12.
- **d.** between 3:12 and 9:12.
- **e.** none of the above.

5. An asphalt shingle roof is generally not permitted if the roof slope exceeds
- **a.** 12:12.
- **b.** 15:12.
- **c.** 18:12.
- **d.** 21:12.
- **e.** 24:12.

6. The roof underlayment commonly used in steep roofs is
- **a.** No. 1 asphalt-treated fiberglass felt.
- **b.** No. 15 asphalt-treated organic felt.
- **c.** No. 30 asphalt-treated organic felt.
- **d.** (a) and (b).
- **e.** (b) and (c).

7. At the eave of an asphalt shingle roof,
- **a.** a drip edge is installed before installing roof underlayment.
- **b.** a drip edge is installed after installing roof underlayment.
- **c.** a drip edge is not required.

8. On the rake of an asphalt shingle roof,
- **a.** a drip edge is installed before installing roof underlayment.
- **b.** a drip edge is installed after installing roof underlayment.
- **c.** a drip edge is not required.

9. Asphalt shingles are generally laid in
- **a.** single coverage with a 5-in. overlap between the top and the bottom shingles.
- **b.** double coverage with a 2-in. overlap between the top and the bottom shingles.
- **c.** double coverage with a 2-in. headlap between the top and the bottom shingles.
- **d.** triple coverage with no headlap.
- **e.** none of the above.

34.4 VALLEY TREATMENT IN AN ASPHALT SHINGLE ROOF

A valley occurs where two pitched roofs meet and water converges. In asphalt shingle roofs, any one of the following three types of valley treatments may be used:

- Open valley
- Woven valley (also called *closed valley*)
- Closed-cut valley

Regardless of the type of valley, each valley requires:

- Valley underlayment
- Valley flashing

Although the flashing material varies with the type of valley, the underlayment requirement for each valley is the same. A valley underlayment consists of a full-width (36-in.-wide) asphalt-treated organic felt (No. 15 or heavier) laid with the center of the roll laid on the

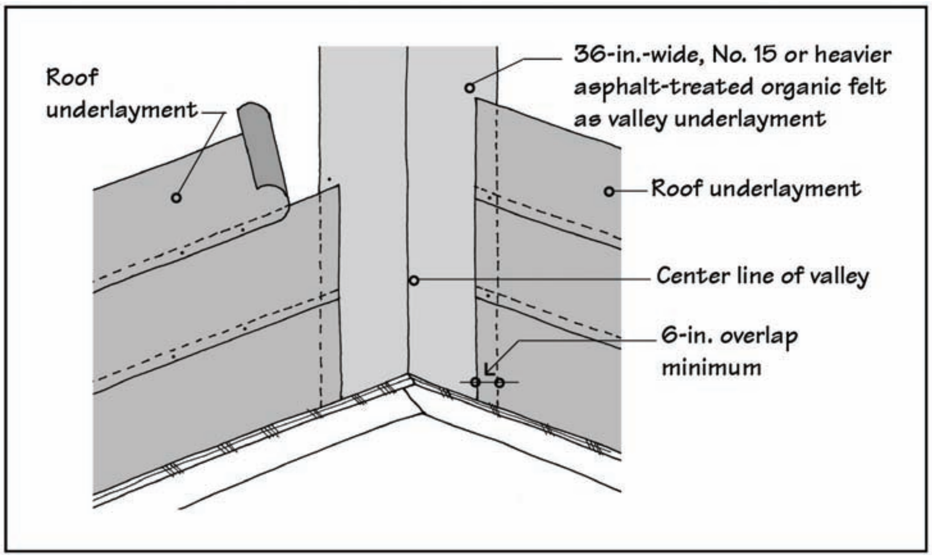

Roof underlayment
36-in.-wide, No. 15 or heavier asphalt-treated organic felt as valley underlayment
Roof underlayment
Center line of valley
6-in. overlap minimum

FIGURE 34.14 Valley underlayment and roof underlayment.

centerline of the valley, Figure 34.14. A self-adhering ice dam protection membrane below the valley underlayment is helpful because valleys are common sources of roof leaks.

Like the roof underlayment, the valley underlayment is also secured with a minimum number of nails. Roof underlayment from the field of the roof is cut so that it overlaps the valley underlayment by a minimum of 6 in. Some roofers prefer to use a self-adhering ice dam protection membrane as the valley underlayment.

OPEN VALLEY—ROLL ROOFING MATERIAL AS VALLEY FLASHING

In an open valley, the shingles are held away from the centerline of the valley so that the valley flashing is exposed to view. An open valley provides a relatively smooth and more rapid discharge of water.

The flashing in an open valley may consist of either roll roofing material or sheet metal. The construction of an open valley using roll roofing material as valley flashing is shown in Figure 34.15. Roll roofing material is an asphalt-treated organic felt with one smooth surface and the other surface covered with mineral granules.

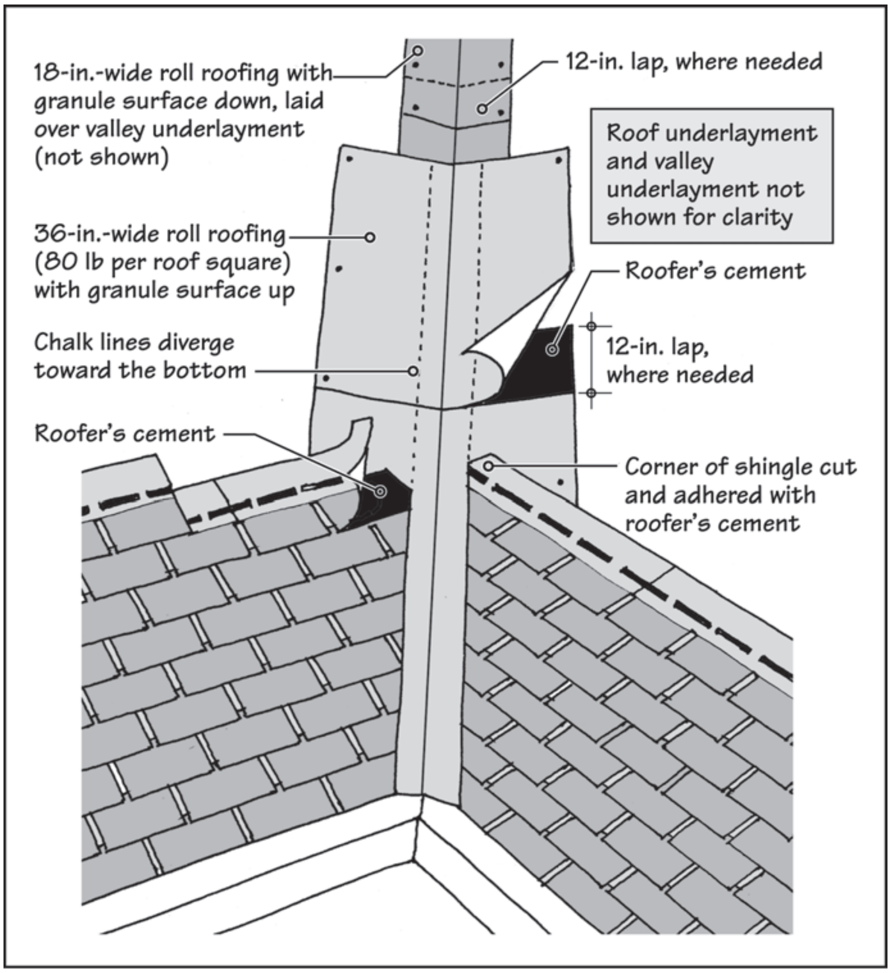

18-in.-wide roll roofing with granule surface down, laid over valley underlayment (not shown)
12-in. lap, where needed
Roof underlayment and valley underlayment not shown for clarity
36-in.-wide roll roofing (80 lb per roof square) with granule surface up
Roofer's cement
12-in. lap, where needed
Chalk lines diverge toward the bottom
Roofer's cement
Corner of shingle cut and adhered with roofer's cement

FIGURE 34.15 Open-valley flashing with roll roofing material used as valley flashing.

Roll roofing valley flashing consists of two layers of felt. The first layer, which is laid immediately over the valley underlayment, is an 18-in.-wide roll roofing felt with the mineral granule surface facing down. The second layer consists of the same material, but it is 36 in. wide. It is laid over the first layer with the mineral granule surface facing up. Both layers of roll roofing are secured with a minimum number of nails or staples.

The width of the exposed part of the valley flashing should increase at the rate of $\frac{1}{8}$ in. per ft toward the bottom of the valley. In practice, this is achieved by placing chalk lines over the valley flashing that converge upward. The minimum width of the exposed part of the valley flashing at the top is 6 in. Thus, if the valley is 24 ft long, the minimum width of the exposed part of the valley flashing at the bottom is 9 in.

The shingles are trimmed along the chalk lines. The end and corner of each shingle adjacent to the valley are cut and adhered with roofer's cement to prevent water from entering under the shingles.

OPEN VALLEY—SHEET-METAL VALLEY FLASHING

The construction of an open valley using sheet-metal flashing is similar to that using roll roofing flashing. The sheet metal generally consists of a minimum of 24-gauge galvanized steel and must be at least 24 in. wide. It is placed over the valley underlayment, Figure 34.16(a). It is typically not nailed, but secured with special metal clips that allow the sheet metal to expand and contract, Figure 34.16(b). Sheet-metal flashing should be used in lengths of no more than 12 ft to reduce their expansion and contraction.

The metal clips, which are located at 8 in. to 24 in. on center, grip the sheet-metal flashing at one end. The other end of the clip is nailed to the deck and then folded over to cover the nails. This protects the shingles against damage by any back-out of the nails.

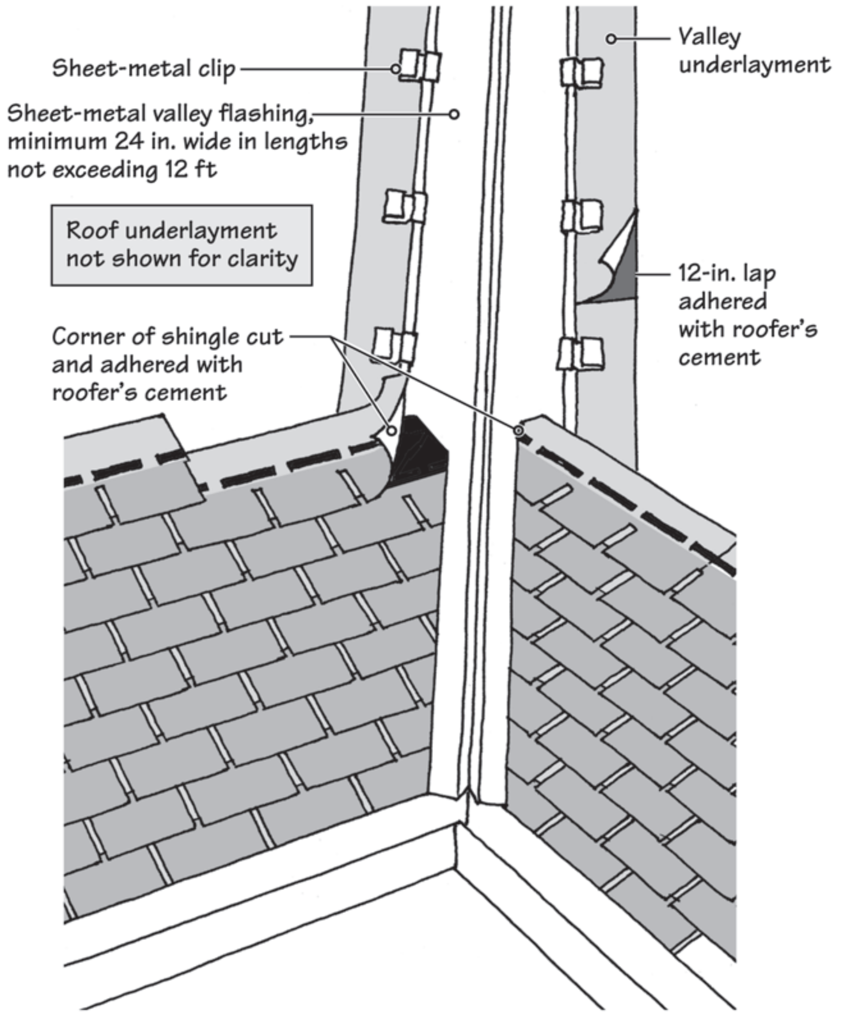
Although the fastening of metal flashing with clips is generally recommended, the clips can telegraph through a lightweight shingle roof, adversely affecting the roof's appearance and performance. In such a case, sheet-metal flashing may be nailed at the roof's outer edges. The outer edges may then be stripped in with a self-adhering ice dam protection membrane.

However, nailing sheet-metal flashing can be problematic in regions with large daily or annual temperature variations. That is why an open-valley sheet-metal flashing is generally not recommended in such areas.

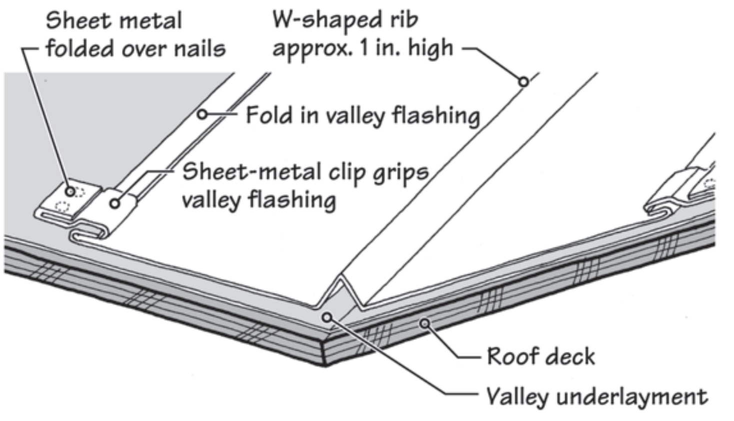
Sheet-metal flashing is generally profiled to form a W-shaped rib in the center. This reduces the crossover of water from one side of the roof to the other.

WOVEN VALLEY

In a woven valley, shingles from the two adjacent roofs weave into each other, covering the valley flashing, Figure 34.17. Because of the weaving of shingles, the thickness of roofing material in a woven valley is greater than in an open valley. Therefore, a woven valley is more durable. It can better withstand the traffic of roofers—who tend to walk in the valley because the valley's slope is lower than that of the adjoining areas of the roof.


Sheet-metal clip
Valley underlayment
Sheet-metal valley flashing, minimum 24 in. wide in lengths not exceeding 12 ft
Roof underlayment not shown for clarity
12-in. lap adhered with roofer's cement
Corner of shingle cut and adhered with roofer's cement

(a) Open valley with sheet-metal valley flashing


Sheet metal folded over nails
W-shaped rib approx. 1 in. high
Fold in valley flashing
Sheet-metal clip grips valley flashing
Roof deck
Valley underlayment

(b) Anchorage of sheet-metal valley flashing

FIGURE 34.16 Open valley in an asphalt shingle roof with sheet-metal valley flashing.

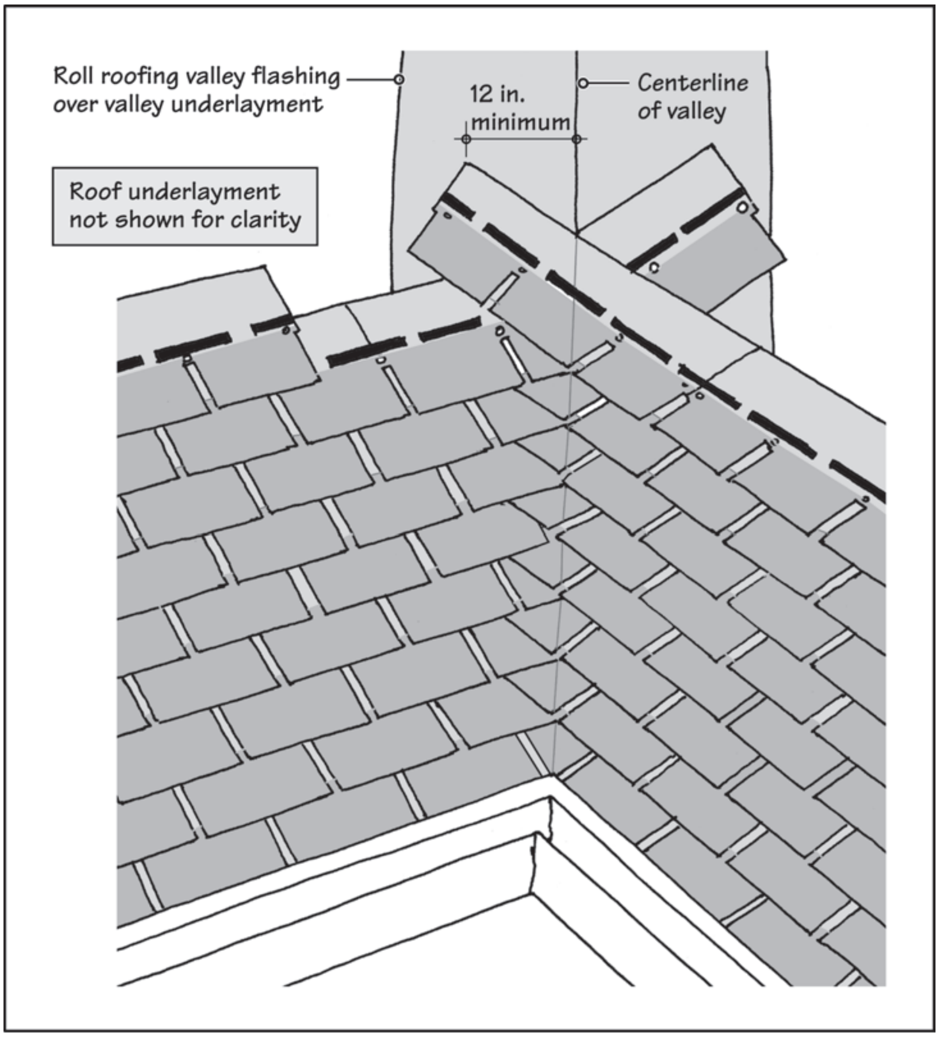

Roll roofing valley flashing over valley underlayment
12 in. minimum
Centerline of valley
Roof underlayment not shown for clarity

FIGURE 34.17 A woven valley in an asphalt shingle roof.

A woven valley, however, does not work well with heavier-weight laminated shingles because these shingles do not bend as much.

The valley flashing in a woven valley consists of roll roofing material and is identical to that provided in an open valley. However, the 18-in.-wide roll roofing sheet shown in Figure 34.15 may be omitted, using only the 36-in.-wide sheet. Sheet-metal valley flashing is not to be used in a woven valley.

Once the valley flashing has been installed, shingles are laid, starting from the eave upward. The shingles extend to the opposite side of the valley by at least 12 in.

CLOSED-CUT VALLEY

In a closed-cut valley, the shingles from one side of the valley are cut parallel to the line of the valley so that the valley is partially closed, Figure 34.18. A closed-cut valley combines the advantages and disadvantages of the other two valley types and is more commonly used. It is more resistant to roofers' traffic than an open valley but less than that of a woven valley.

Valley flashing in a closed-cut valley is identical to that in a woven valley. The shingles from one side of the valley extend to the opposite side by a minimum of 12 in. However, the shingles from the other side are trimmed parallel to the centerline of the valley, leaving an overlap of 2 in.

34.5 RIDGE AND HIP TREATMENT IN AN ASPHALT SHINGLE ROOF

Asphalt shingles from both sides of a ridge are butted against each other at the ridge, which is then capped with ridge shingles. Some manufacturers provide special ridge shingles, but these can also be prepared on site from standard shingles. To do so, a shingle is field trimmed along dashed lines, Figure 34.19. The dashed lines taper slightly away from the cutouts. The trimming converts a three-tab shingle into three nearly 12-in. × 12-in. shingles.

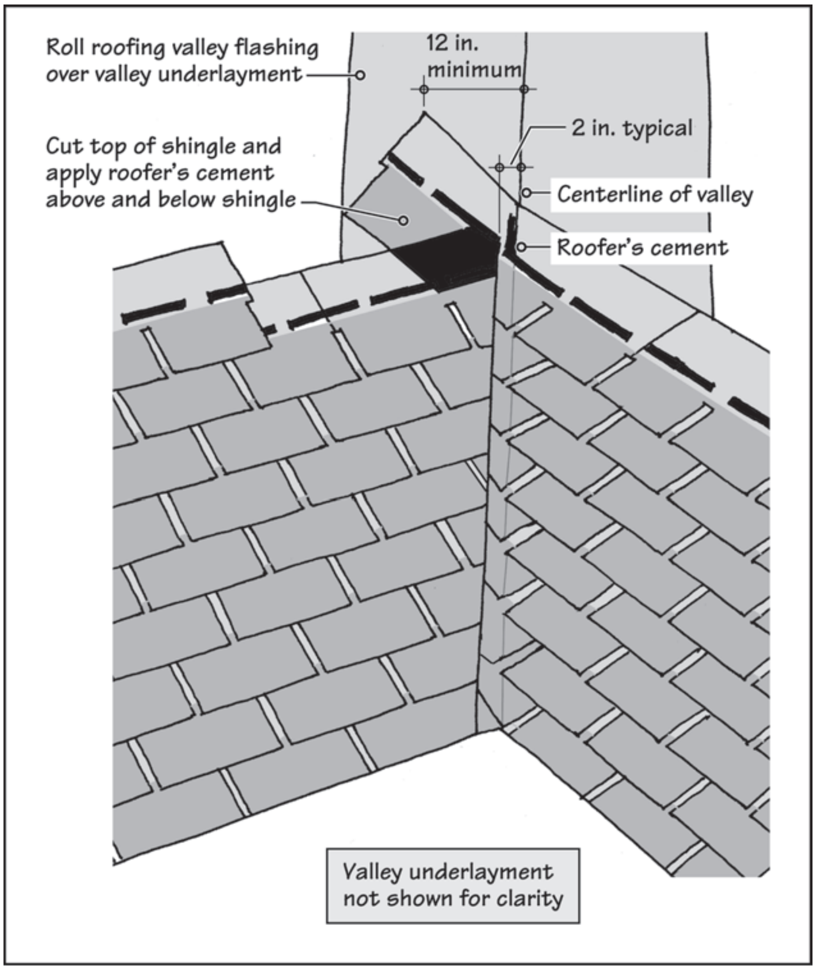

Roll roofing valley flashing over valley underlayment
12 in. minimum
2 in. typical
Cut top of shingle and apply roofer's cement above and below shingle
Centerline of valley
Roofer's cement
Valley underlayment not shown for clarity

FIGURE 34.18 A closed-cut valley.

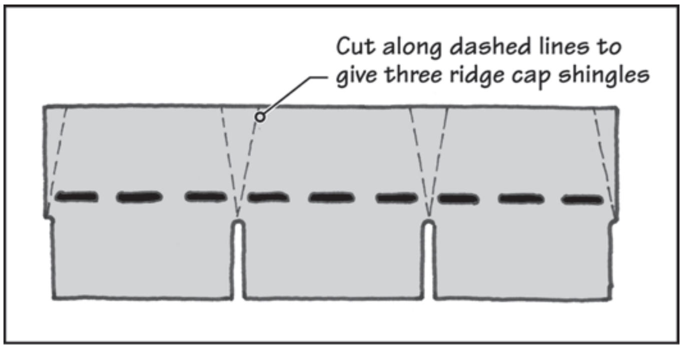

Cut along dashed lines to give three ridge cap shingles

FIGURE 34.19 Creating ridge (or hip) caps from a standard three-tab shingle.

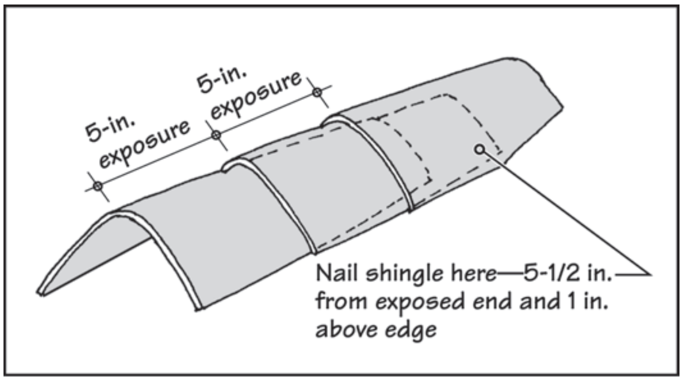

5-in. exposure
5-in. exposure
Nail shingle here—5-1/2 in. from exposed end and 1 in. above edge

FIGURE 34.20 Layout and nailing of ridge cap shingles.

These smaller shingles are now bent and nailed over the ridge as caps, using a 5-in. exposure, Figure 34.20. In cold weather, the shingles may be warmed somewhat to increase their pliability, because fiberglass shingles are generally brittle.

The treatment of a hip is similar to that of a ridge. The hip is capped with the same shingles as a ridge, and the shingles are installed from the bottom of the hip to the top, Figure 34.21.

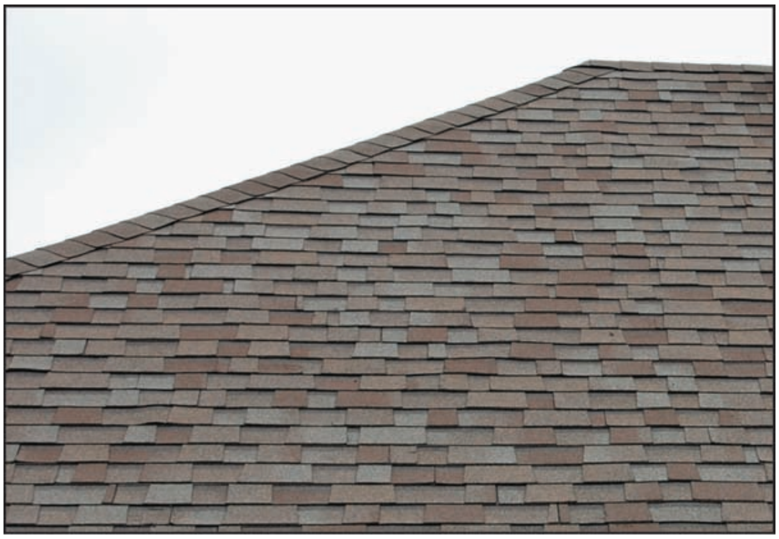


FIGURE 34.21 An asphalt shingle roof showing hip cap shingles and ridge cap shingles. Note that the two types of shingles are identical.

34.6 FLASHINGS IN AN ASPHALT SHINGLE ROOF

A sloping roof plane that abuts a vertical side wall is flashed with metal shingles placed over the end of each asphalt shingle course—a flashing system referred to as *step flashing*. Metal shingle flashing is made of galvanized or prepainted sheet steel.

The profile of a metal shingle flashing is an L shape, each leg at least 5 in., so that the shingle flashing extends 5 in. in both horizontal and vertical directions. The length of shingle flashing is 2 in. greater than the exposure of roof shingles. Thus, with the most commonly used three-tab roof shingles that have a 5-in. exposure, 7-in.-long metal shingle flashing is commonly used. With its 7-in. length and 5-in. exposure, each metal shingle flashing overlaps the underlying shingle flashing by 2 in., Figure 34.22.

Each shingle flashing piece is placed slightly upslope of the exposed edge of the roofing shingle that overlaps it. In other words, the horizontal surface of metal shingles is not visible, and each metal shingle flashing is completely covered by the overlying roof shingle. Each shingle flashing piece is secured to the deck by two nails placed at its top edge; the vertical leg of a shingle flashing is not fastened. Metal shingle flashing is counterflashed by siding that terminates 2 in. above the roof surface.

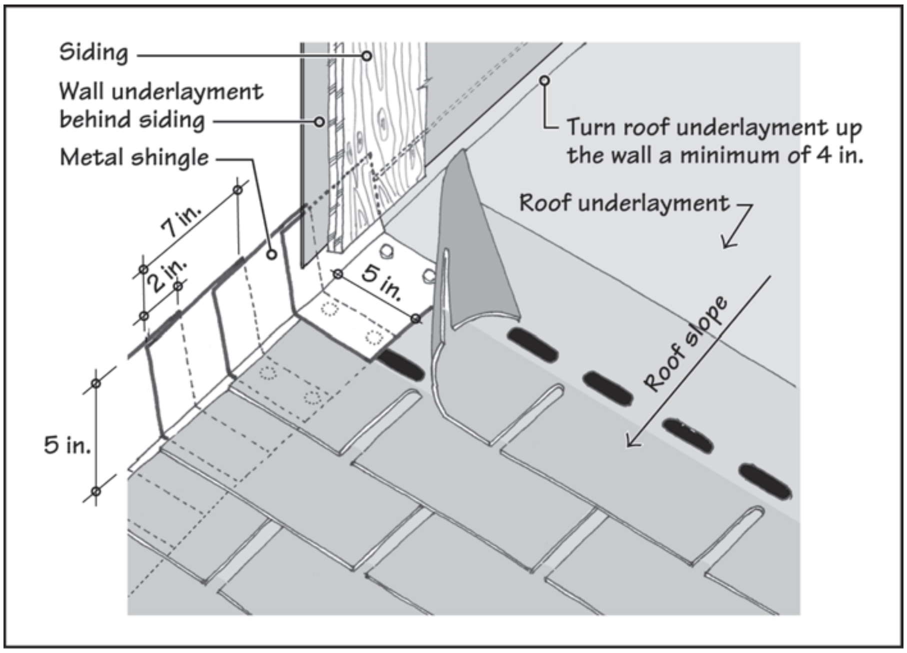

Siding
Wall underlayment behind siding
Metal shingle
Turn roof underlayment up the wall a minimum of 4 in.
Roof underlayment
7 in.
2 in.
5 in.
5 in.
Roof slope

FIGURE 34.22 Step flashing against a wall that abuts the sloping side of an asphalt shingle roof.

FLASHING AROUND A MASONRY CHIMNEY

Flashing around a masonry chimney consists of the following four-component sheet-metal flashings, where the sheet metal is generally prepainted steel or any other compatible metal:

- Apron flashing
- Step flashing
- Cricket flashing
- Counterflashing

Sheet-metal apron flashing is placed over the downslope side of chimney and tightly wrapped around it, Figure 34.23(a). This requires prefabricating the flashing to a profile, shown in Figure 34.23(b), and adhering it to the chimney with roofer's cement.

After the apron flashing has been applied, step flashing is installed on the side walls of the chimney in the same way shown in Figure 34.22. Note that the first step-flashing shingle wraps over the apron flashing at the corner by at least 2 in., Figure 34.24. Step flashing is also set with roofer's cement applied to chimney walls.

The upslope side (backside) of a chimney requires a cricket. Thus, before installing any metal flashing, roof shingles, or a roof underlayment around a chimney, a cricket is formed with plywood or oriented strandboard, Figure 34.25. Roof underlayment is subsequently installed on the deck and over the ice dam protection membrane. (Because a chimney is one of the primary sources of leaks on an asphalt shingle roof, a self-adhering ice dam protection membrane should preferably be installed all around the base of the chimney, with its edges turned up the chimney walls.)

The flashing over the cricket consists of a prefabricated sheet-metal flashing, Figure 34.26. The joints in cricket flashing are thoroughly soldered. The chimney is then ready to receive sheet-metal counterflashing, Figure 34.27.

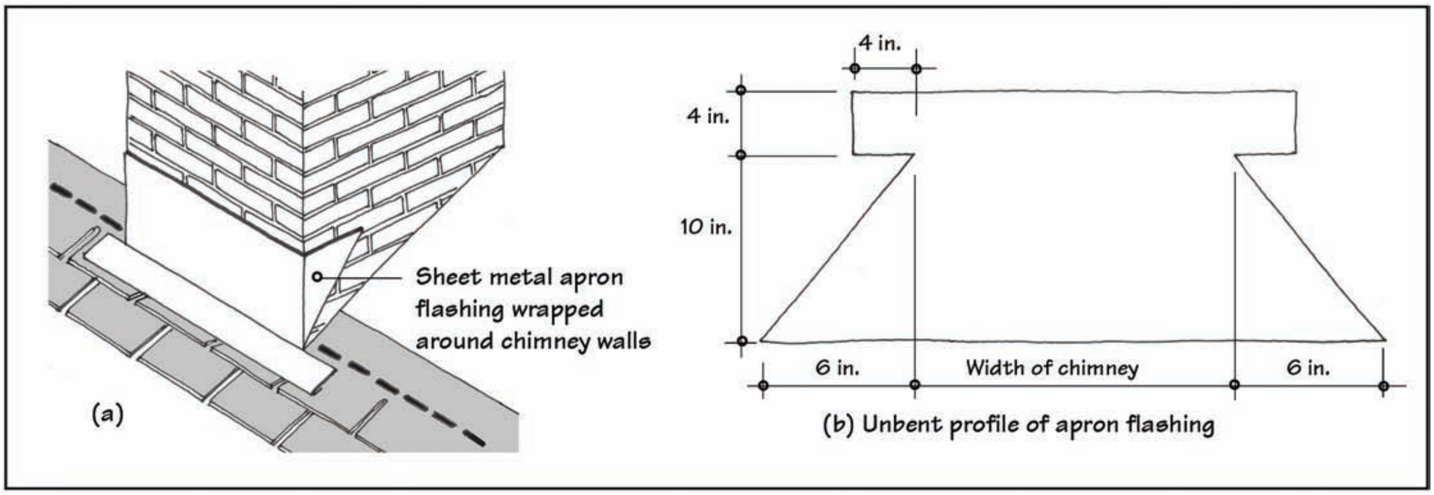

Sheet metal apron flashing wrapped around chimney walls
(a)
4 in.
4 in.
10 in.
6 in.
Width of chimney
6 in.
(b) Unbent profile of apron flashing

FIGURE 34.23 Apron flashing on the front face of chimney.

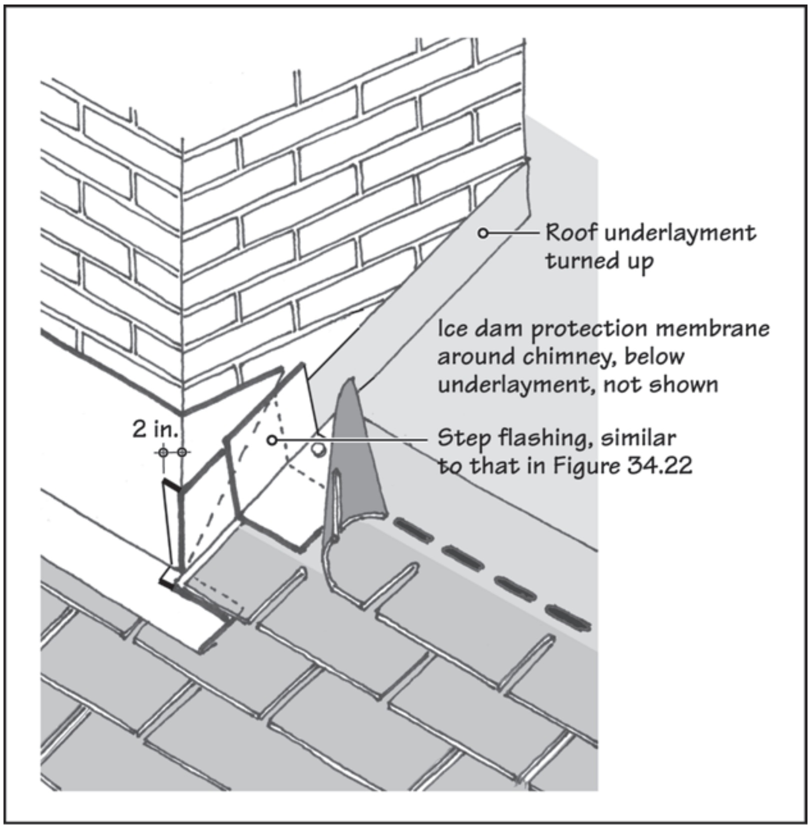

Roof underlayment turned up
Ice dam protection membrane around chimney, below underlayment, not shown
2 in.
Step flashing, similar to that in Figure 34.22

FIGURE 34.24 Step flashing on the side walls of a masonry chimney.

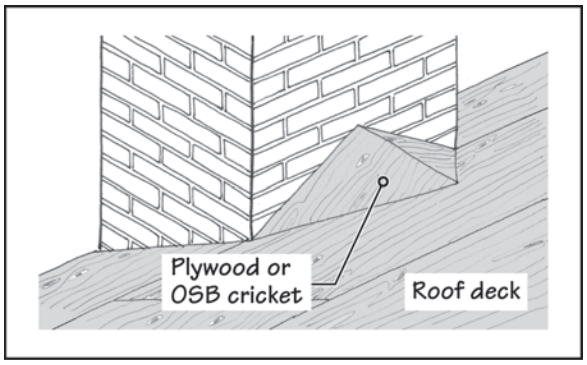

Plywood or OSB cricket
Roof deck

FIGURE 34.25 Formation of a plywood or OSB cricket on the upslope side (back) of a chimney wall.

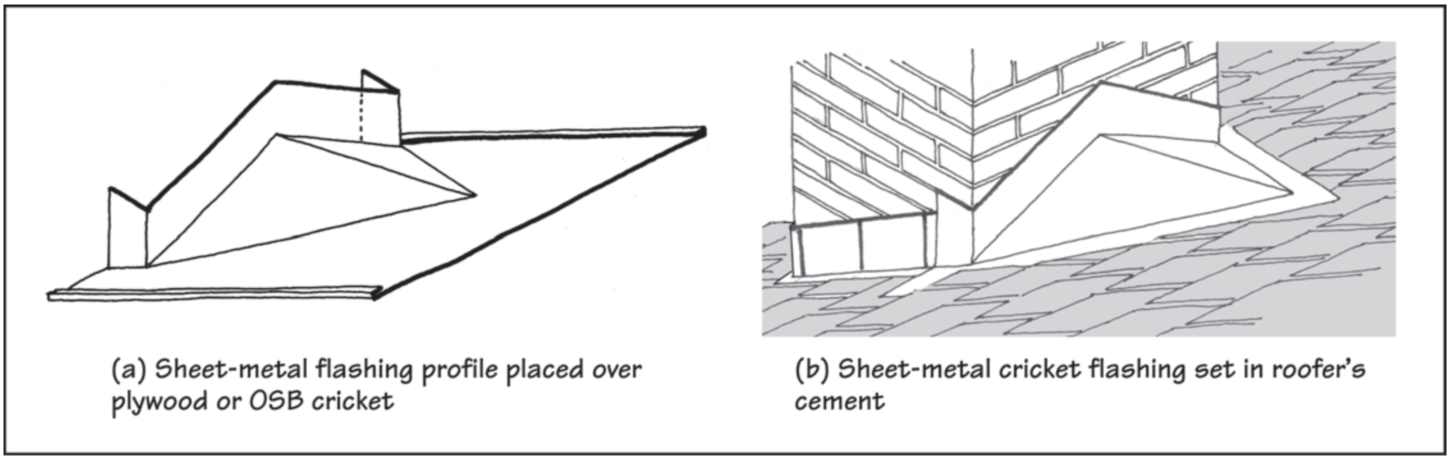

(a) Sheet-metal flashing profile placed over plywood or OSB cricket
(b) Sheet-metal cricket flashing set in roofer's cement

FIGURE 34.26 Sheet-metal cricket flashing.

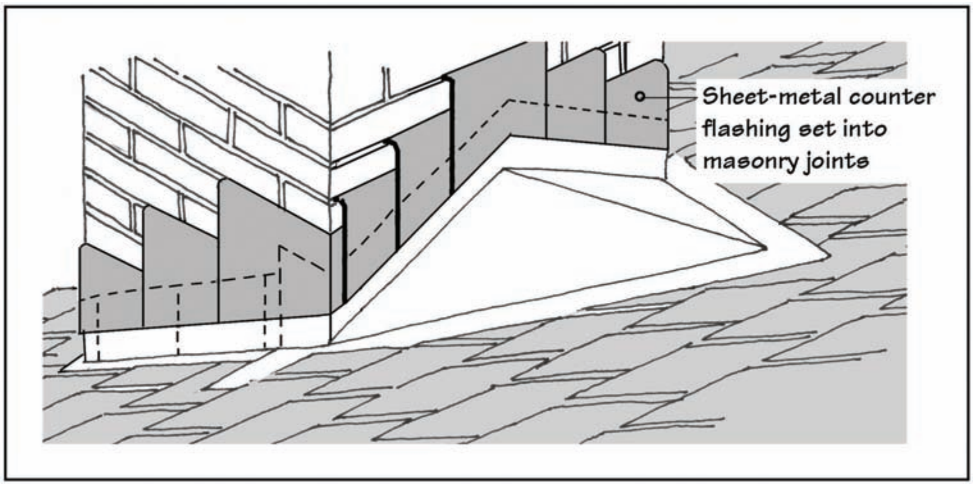

Sheet-metal counter flashing set into masonry joints

FIGURE 34.27 Counter flashing over chimney wall, set into masonry joints as shown in Figure 34.28.

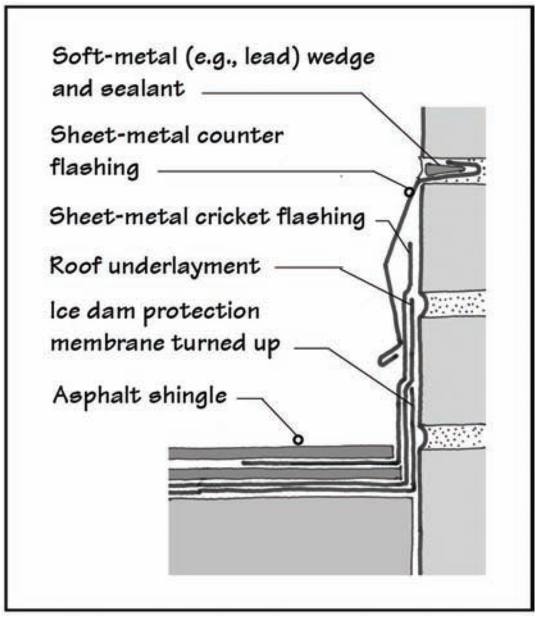

Soft-metal (e.g., lead) wedge and sealant
Sheet-metal counter flashing
Sheet-metal cricket flashing
Roof underlayment
Ice dam protection membrane turned up
Asphalt shingle

FIGURE 34.28 Section through counter flashing.

Counterflashing is generally of the same metal as the flashing. One edge of the counterflashing laps over the flashing, and the other edge is inset into the masonry mortar joints, Figure 34.28. This requires cutting the appropriate mortar joints to a depth of nearly 1.5 in.—a cut that is commonly referred to as a *raggle*. The inset edge of counter-flashing is profiled to fit into the raggle, giving a friction fit. Counterflashing is further secured by driving a soft-metal (e.g., lead) wedge into the raggle and finishing the joint with an elastomeric sealant.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

10. In an asphalt shingle roof, roof underlayment is installed first, followed by valley underlayment.
a. True **b.** False

11. In an asphalt shingle roof, either valley underlayment or valley flashing is used.
a. True **b.** False

12. In an asphalt shingle roof, sheet-metal valley flashing is used in an
a. open valley. **b.** closed-cut valley.
c. woven valley. **d.** all of the above.
e. (a) and (b) only.

13. In an asphalt shingle roof, the ridge and hip are capped with shingles. The ridge cap and hip cap shingles can be used interchangeably.
a. True **b.** False

14. The junctions between the walls of a chimney and a steep roof need to be flashed. Which of the following flashings is required as chimney flashing?
a. Step flashing **b.** Apron flashing
c. Cricket flashing **d.** All of the above
e. Only (a) and (c)

15. In an asphalt shingle roof, which of the following flashings is interwoven with shingles?
a. Step flashing **b.** Apron flashing
c. Cricket flashing **d.** All of the above
e. Only (a) and (c)

16. In a steep roof, which of the following flashings is made from sheet metal?
a. Step flashing **b.** Apron flashing
c. Cricket flashing **d.** All of the above
e. Only (a) and (c)

17. Which of the following flashings in a steep roof has the shape of a small, steep roof?
a. Step flashing **b.** Apron flashing
c. Cricket flashing **d.** All of the above
e. Only (a) and (c)

34.7 ESSENTIALS OF CLAY AND CONCRETE ROOF TILES

The service life spans of concrete and clay tile roofs are significantly longer than that of asphalt shingle roofs. Because of their color, texture, and tile profile, they produce handsome-looking roofs. That is why in modern construction, concrete and clay tiles are extensively used in low-rise commercial structures and higher-priced homes and apartment buildings.

TYPES OF CLAY AND CONCRETE ROOF TILES

Tiles come in a large variety of profiles, sizes, and colors, depending on the manufacturer. The clay tile's color is primarily a function of the chemical composition of the clay from which it is made. If any additional color-modifying agent is used, it is added to the clay before firing. Therefore, the color becomes integral to the tile. With its integral color, clay tile weathers only slightly with time, caused mainly by the pollutants in the air. Glaze-coated clay tiles are also available. The glaze is applied to the already-fired tiles, which are then refired to obtain a durable glaze.

The color of concrete tiles is a function of the color of the Portland cement, aggregates, and any pigments used. The gradual erosion of the surface of the tile due to running water on the roof exposes the aggregates in a concrete tile, which can create a noticeable change in the tile's color over time. Initial and periodic sealing of the tiles' surface helps retain the color longer.

Concrete tiles can also be factory painted on their exposed surface. Several manufacturers make concrete tiles with the characteristic (brown) terra-cotta color painted on them to mimic clay tiles. Being an applied finish, the paint tends to fade over time.

CLAY AND CONCRETE ROOF TILE PROFILES

Because of the enormous variety in the profiles of concrete and clay tiles, it is impossible to discuss all available profiles. Although some profiles are used only with clay tiles and others only with concrete tiles, most tile profiles are essentially similar. Except for flat tile, all tile profiles provide for water channels that direct water down the roof. That is why roof tiles are generally laid in single coverage with a simple overlap of 3 in. between succeeding courses. This is unlike asphalt shingle roofs, which are laid in double coverage with a 2-in. headlap.

One of the oldest profiles, and a commonly used one in clay tiles, is the *mission tile*, which consists of an almost semicircular barrel profile. The tiles are laid alternately, one tile in a water-holding setting (pan) and the other tile in a water-shedding setting (cover), Figure 34.29. Both pan and cover tiles are provided with one hole to receive a fastener at the head of each tile.

Another commonly used clay tile profile is a derivative of the mission tile. Called an *S-shape tile*, a *one-piece barrel*, or an *S-shape mission tile*, it integrates the pan and cover of the mission tile into one unit, Figure 34.30. The S-shape tile generally comes with its two opposite ends chamfered to allow for easier drainage of water. The chamfer is generally of the same size as the overlap needed between the adjacent tiles to give a better, more exact fit between them. Each tile is provided with two fastener holes at its head.

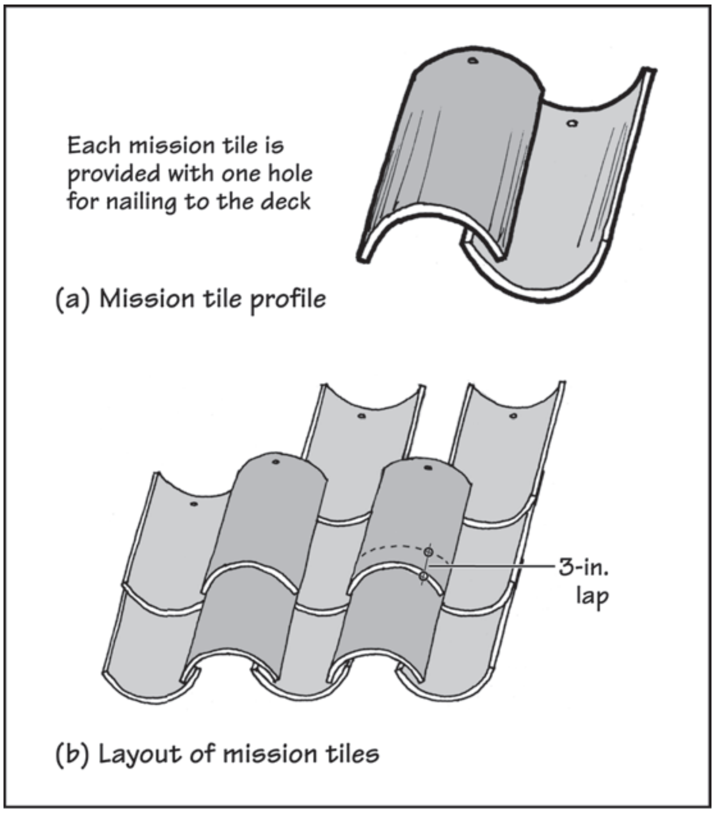

Each mission tile is provided with one hole for nailing to the deck
(a) Mission tile profile
3-in. lap
(b) Layout of mission tiles

FIGURE 34.29 Mission tile profile and layout.

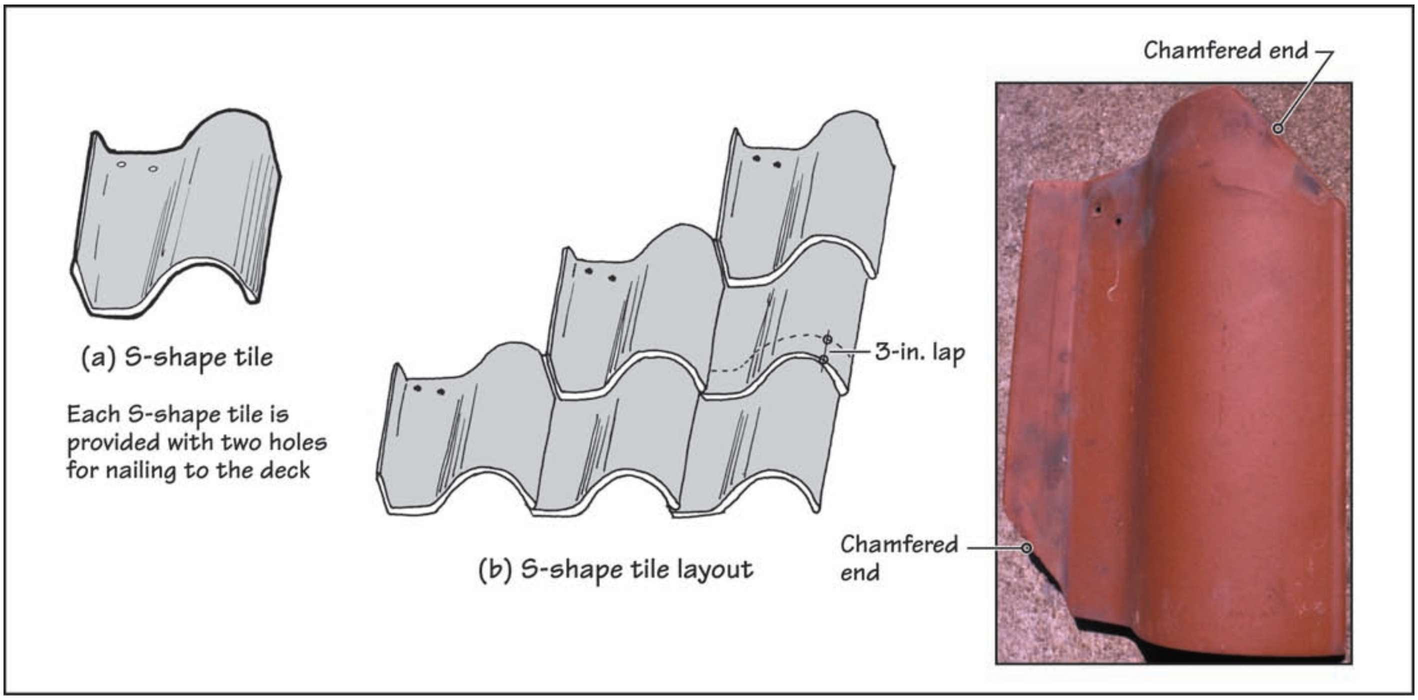


FIGURE 34.30 S-shape tile and its layout.

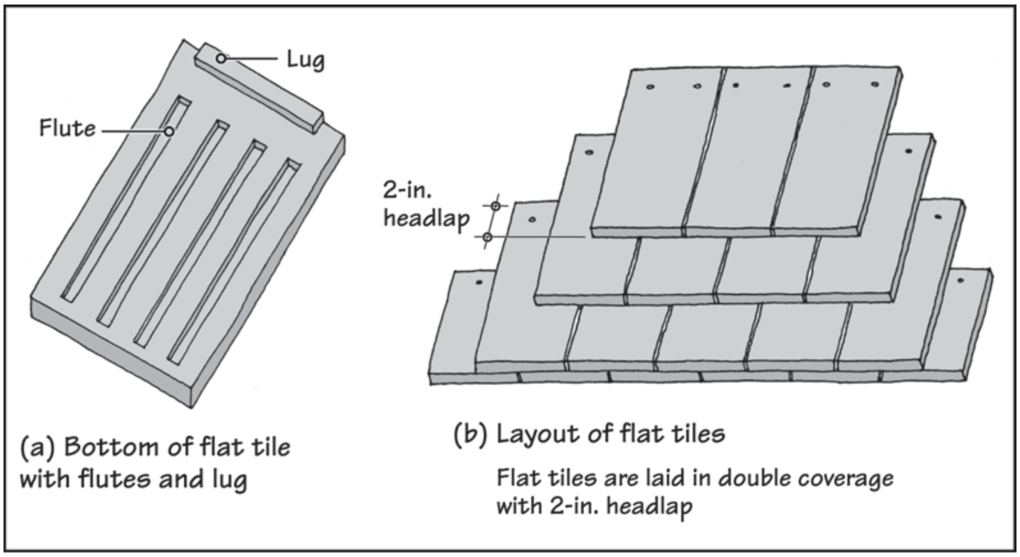

Lug
Flute
2-in. headlap
(a) Bottom of flat tile with flutes and lug
(b) Layout of flat tiles
Flat tiles are laid in double coverage with 2-in. headlap

FIGURE 34.31 Flat tile and its layout.

Other profiles include a flat tile. Flat tiles are laid like asphalt shingles or slates—in double coverage and with a headlap of 2 in., Figure 34.31. That is why they are also referred to as *shingle tiles*. Because of its double coverage, the weight of a shingle tile roof is higher than that of roofs constructed of curved roof tiles.

WATER ABSORPTION AND STRENGTH OF TILES

Unlike asphalt shingles, concrete and clay tiles absorb water. Water absorption increases the weight of the tile roof and leads to freeze-thaw damage of tiles. It also increases the color-degradation tendency as the water-soluble pollutants enter the body of the tile. Less porous tiles are obviously better but are more expensive.

The porosity of clay tiles varies from 2% to 10%; that of concrete tiles, from 3% to 20%. Sealers are generally used to reduce the effect of porosity. The service life of the sealers and the cost of repeat applications must be considered in tile selection. It may be more economical in the long run to specify a denser, albeit more expensive, tile.

Some tiles are graded (Grades 1, 2, or 3) for their freeze-thaw resistance. Grade 1 is typically specified in severe freeze-thaw climates, Grade 2 in moderate freeze-thaw climates, and Grade 3 in climates with negligible freeze-thaw activity.

Porosity is not merely an index of the tile's water absorptivity; it also indicates the tile's strength. A more porous tile is weaker. Strength is an important selection criterion for concrete and clay tiles, because a stronger tile is generally more durable.

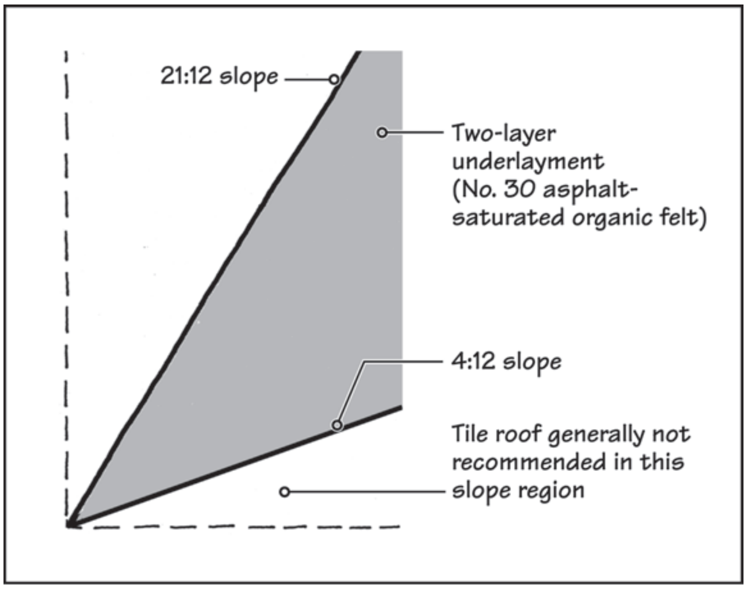

21:12 slope
Two-layer underlayment (No. 30 asphalt-saturated organic felt)
4:12 slope
Tile roof generally not recommended in this slope region

FIGURE 34.32 Roof slope and recommended underlayment for tile roofs.

ROOF UNDERLAYMENT AND TILE ROOFS

Because a tile roof is a relatively long-lasting roof, the underlayment should match the durability of the tiles. The following underlayment specifications are generally recommended:

- *For roofs with a slope greater than 4:12:* A minimum of two layers of No. 30 asphalt-saturated felt laid in shingle fashion, Figure 34.32.
- *For roofs with a slope less than 4:12:* Tile roofs are generally not recommended in this slope region, although some manufacturers allow their product for use in this region.

ICE DAM PROTECTION MEMBRANE

An ice dam protection membrane at the eave should be specified in all climates. However, it is particularly important in cold climates. The minimum requirement for an ice dam protection membrane is the same as that for the asphalt shingle roofs.

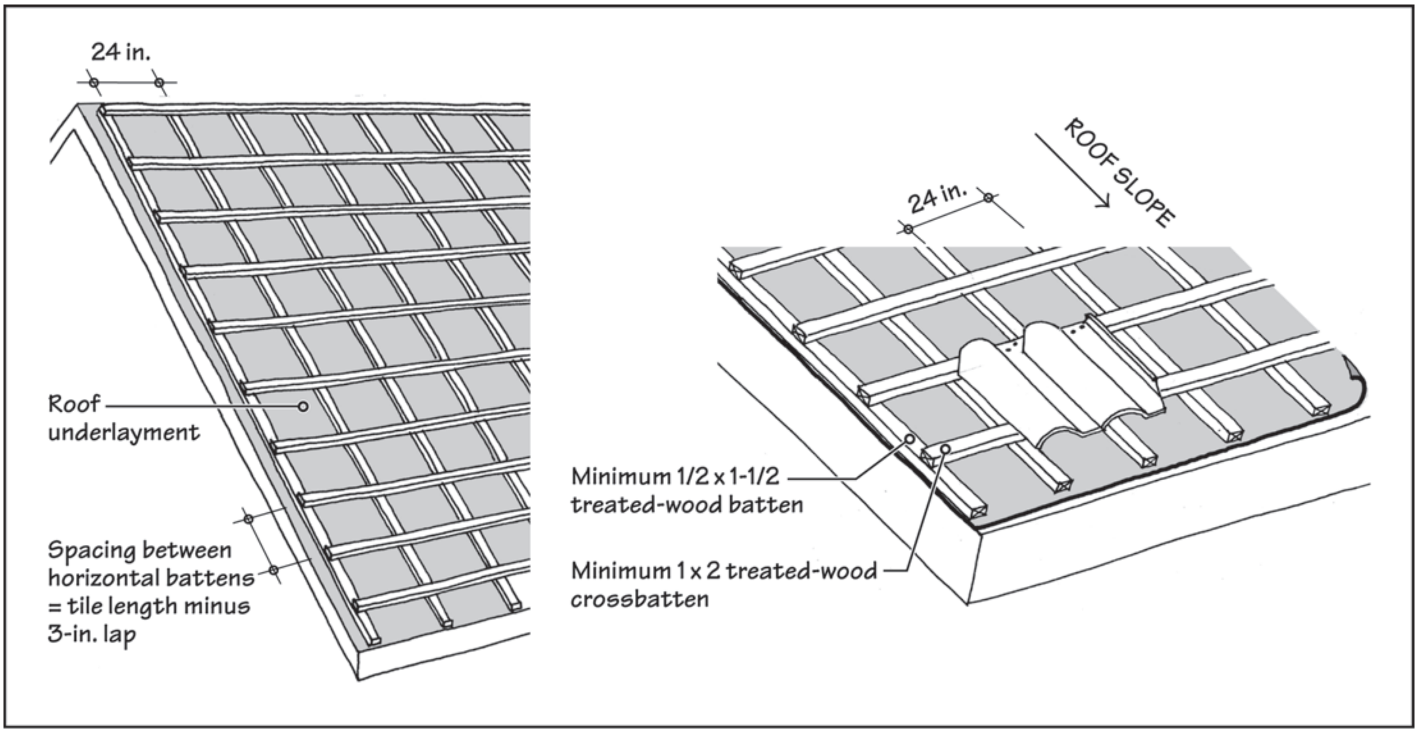

24 in.
Roof underlayment
Spacing between horizontal battens = tile length minus 3-in. lap
ROOF SLOPE
24 in.
Minimum 1/2 x 1-1/2 treated-wood batten
Minimum 1 x 2 treated-wood crossbatten

FIGURE 34.33 Installation of tiles on a network of preservative-treated wood battens and crossbattens.

34.8 CLAY AND CONCRETE TILE ROOF DETAILS

The easiest and most commonly used method of fastening the tiles is to nail them to the substrate. The nails should be of stainless steel or copper to match the long life of a tile roof. Except for mission tiles, other tiles can be nailed straight to the deck. However, the best installation of tiles is achieved if a network of battens and crossbattens of treated wood is nailed to the deck over the underlayment, Figure 34.33. The tiles are then nailed to the (top) battens, which run horizontally. The horizontal battens should be a minimum of 1 in. × 2 in. (nominal), and the vertical battens should be a minimum of $\frac{1}{2}$ in. × $1\frac{1}{2}$ in. (nominal).

The vertical battens are generally laid 24 in. on center. The spacing of the horizontal battens is a function of the length of the tile. Thus, with a 3-in. lap between successive courses, the center-to-center spacing of horizontal battens equals the tile length minus 3 in.

The batten network creates a space under the tiles, which allows for clear drainage of water should the water seep under the tiles. Because the tiles are generally laid in single coverage with only a 3-in. lap, seepage of water under the tiles in severe weather is not uncommon.

The space under the tiles also permits more rapid drying of the underlayment. Battens also help to hang the tiles that consist of lugs. A major advantage of a batten and crossbatten network is that such a system can be used with slopes less than 4:12, provided that the underlayment is treated like a built-up roof. In that case, the tiles serve simply as a decorative roof covering.

In place of the batten and crossbatten network, a system of one-way horizontal battens may be used, Figure 34.34. The battens are generally laid in 4-ft lengths, separated by a minimum of a $\frac{1}{2}$-in. space. The $\frac{1}{2}$-in. separation allows the drainage of any water trapped by the battens. However, this system does not perform as well as the crossbatten system because the dust and debris block the drainage, causing leaks.

In addition to nailing each tile, additional anchorage may be required in a high-wind or high-seismic region, Figure 34.35.

EAVE TREATMENT

Unlike an asphalt shingle roof, the drip edge is not necessary with a tile roof because the eave tiles can be made to project sufficiently beyond the fascia. However, if a drip edge is used, it should be of a durable metal (e.g., 24-oz copper) to match the long life of a tile roof. A treated-wood edge strip is also required at the eave to give the correct alignment to the first tile, Figure 34.36. Tile manufacturers also make starter tiles that preclude the need of an edge strip.

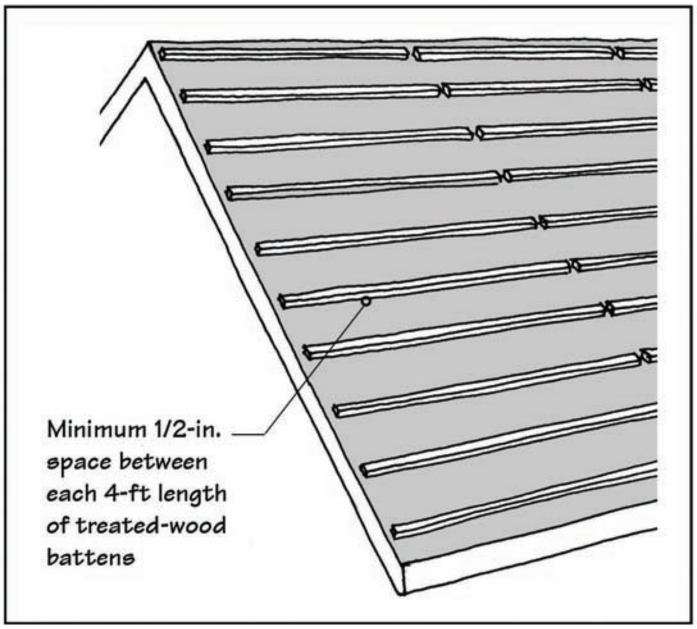

Minimum 1/2-in. space between each 4-ft length of treated-wood battens

FIGURE 34.34 In place of batten and cross batten arrangement of Figure 34.33, one-way battens may be used.

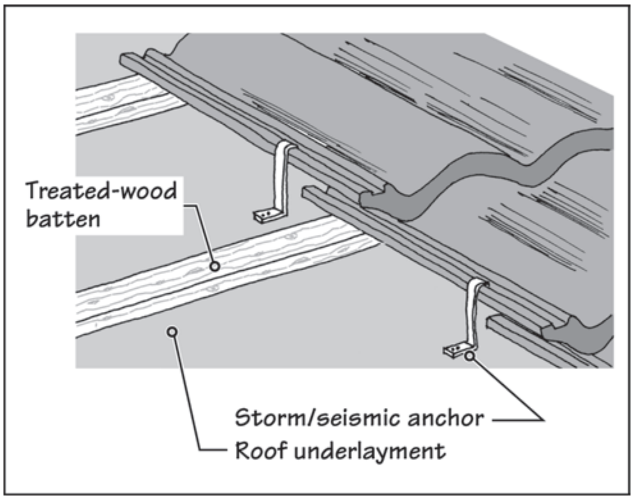

Treated-wood batten
Storm/seismic anchor
Roof underlayment

FIGURE 34.35 Storm or seismic tile anchors.

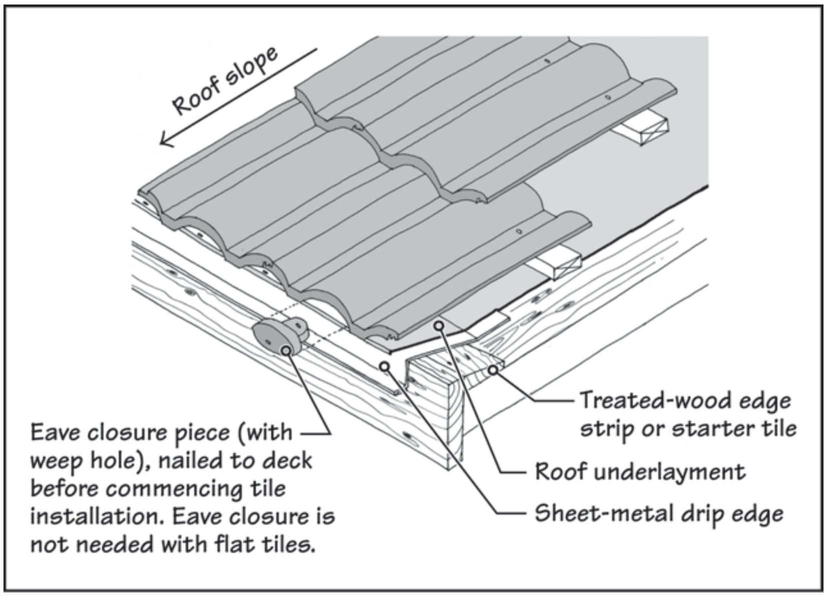

Roof slope
Treated-wood edge strip or starter tile
Eave closure piece (with weep hole), nailed to deck before commencing tile installation. Eave closure is not needed with flat tiles.
Roof underlayment
Sheet-metal drip edge

FIGURE 34.36 Eave treatment of a tile roof.

Eave-closure pieces are required to fill the space between the tiles and the underlying construction. (With flat tiles, eave-closure pieces are obviously not needed.) Closure pieces can be of clay (with clay tiles), concrete, or plastic. They are provided with weep holes to allow the escape of water that may seep under the tiles. The closure pieces are nailed to the deck before the tiles are installed. Closing the space under the tiles prevents the nesting of birds and insects. Portland cement mortar may also be used to fill the gap between the eave tiles and the underlying part of the roof if weep holes are provided in each mortar filling.

RAKE, RIDGE, AND HIP TREATMENTS

Specially prepared (curved) rake tiles are generally used to weatherproof the rake, Figure 34.37(a). The construction of a ridge and a hip is similar. With curved tiles, a treated-wood

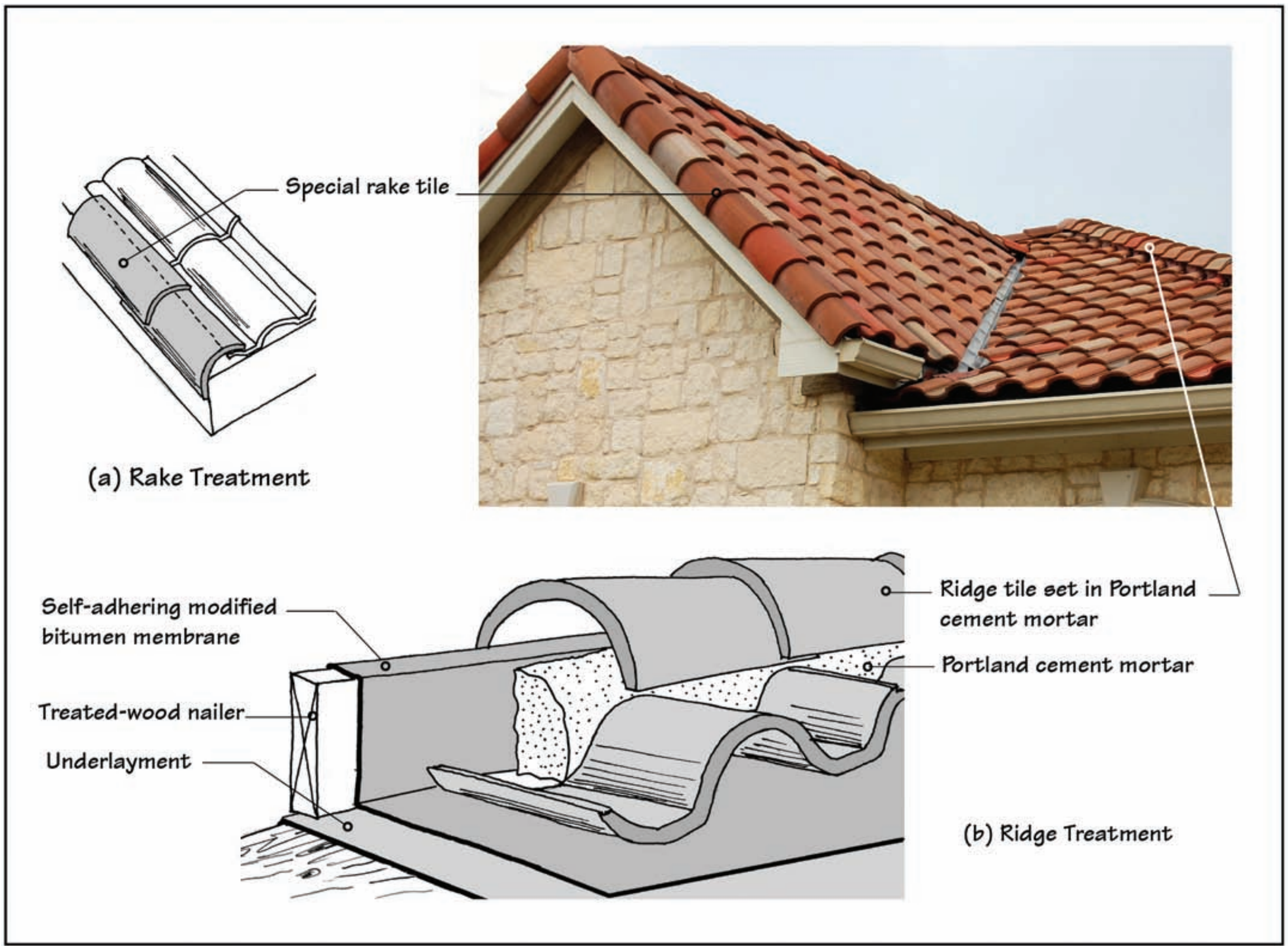

Special rake tile
(a) Rake Treatment
Self-adhering modified bitumen membrane
Treated-wood nailer
Underlayment
Ridge tile set in Portland cement mortar
Portland cement mortar
(b) Ridge Treatment

FIGURE 34.37 Rake and hip treatment of a tile roof. Ridge treatment is similar.

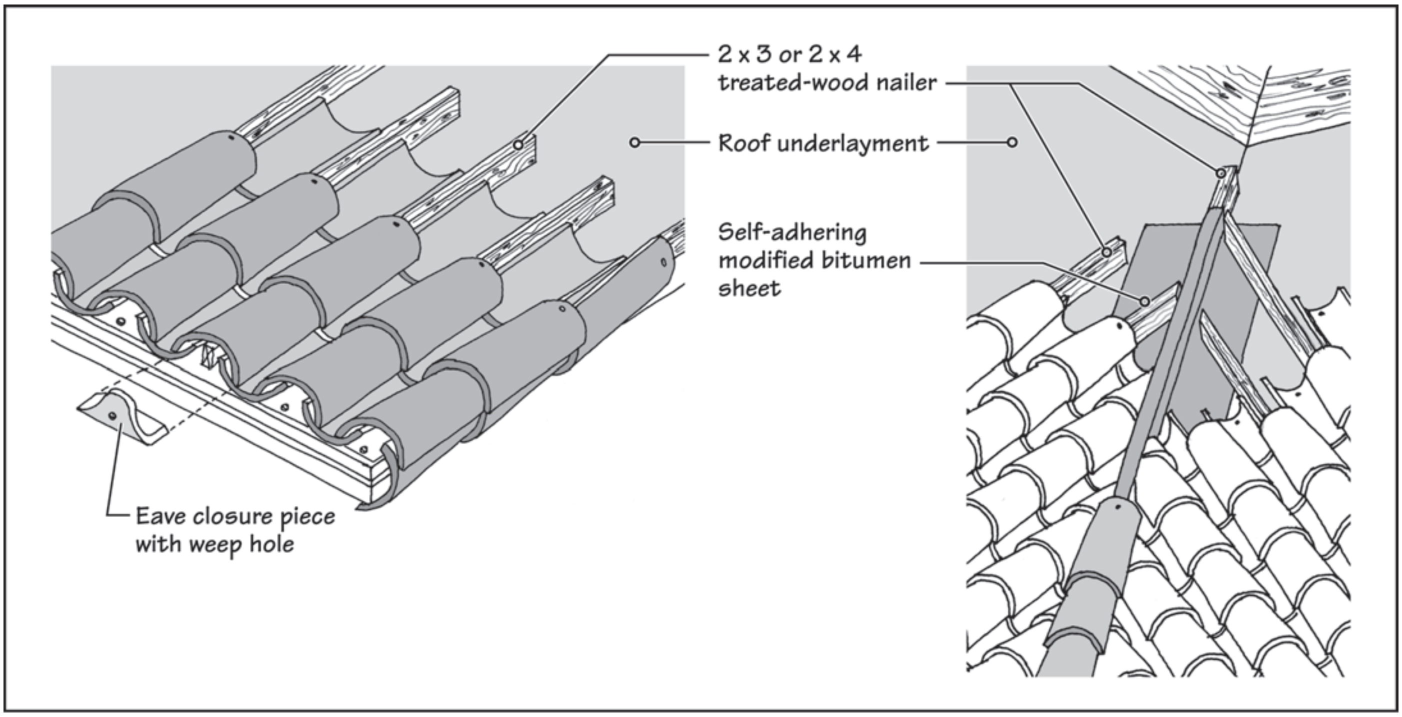


FIGURE 34.38 Installation details of mission tiles.

nailer is installed at the ridge (or the hip), and a self-adhering modified bitumen sheet is wrapped over the nailer. Field tiles are brought close to the nailer, and the nailer is covered with special ridge (or hip) tiles set in Portland cement mortar. The mortar holds the ridge (or hip) tiles and also closes the gap between the ridge tiles (or hip tiles) and the field tiles, Figure 34.37(b). Each ridge (or hip) tile is nailed to the nailer. Although these nails are protected by the overlapping ridge (or hip) tile, it is necessary to seal the nail with roofer's cement or sealant.

INSTALLATION OF MISSION TILES

Mission tiles require an entirely different installation system. A treated-wood nailer, aligned along the slope of the roof, is placed under every cover piece, and the cover piece is nailed to the nailer, Figure 34.38. The nailer is usually either 2 × 3 or 2 × 4 (nominal size), depending on the height of the cover piece. The nailer not only helps to secure the tile, but also reduces the possibility of tile breakage when roofers walk on the tiles. The tiles are laid with 3-in. standard overlap, as with other tiles.

Eave-closure pieces are required, and the rake is covered with the field tiles and rake cover tiles. Additional nailers are needed at the rake. The construction of a ridge or a hip is similar to that of other tile roofs.

34.9 TYPES OF SHEET-METAL ROOFS

Sheet-metal roofs are increasingly becoming part of the urban landscape. The development of durable coatings on sheet steel, coupled with a vast array of nonfading coating colors, has increased the popularity of metal roofs. Metal roofs are spared the rapid atmospheric and solar degradation to which other commonly used low-slope roofs (e.g., built-up, modified bitumen, or single-ply roofs) are subjected.

Some owners of commercial buildings, unhappy with the frequent replacement of their existing low-slope roofs, are switching to metal roofs when reroofing is needed. This is despite the fact that a change from a low-slope roof to a metal roof on an existing building requires many of additional under-roof components. Sheet-metal roofs can be divided into two types:

- Structural sheet-metal roofs
- Architectural sheet-metal roofs

Structural sheet-metal roofs double as a roof covering and also as a structural deck. A separate deck is not provided with such roofs, and the roof panels are supported directly on purlins, which are typically spaced 4 ft to 5 ft on center. Structural metal roofs are commonly used in low-cost industrial buildings in what are generally referred to as *preengineered* *metal buildings*. Preengineered metal buildings use highly standardized manufacturer-specific components and assemblies; a discussion of such roofs is beyond the scope of this text.

Architectural sheet-metal roofs, which are discussed further here, require a supporting deck and an underlayment. Historically, they were limited for use in steep slopes (slope ≥ 3:12), but recently, some manufacturers allow their use in slopes less than 3:12 if sealants are used between overlapping panels. Architectural sheet-metal roofs may be further subdivided into the following types:

- *Traditional architectural metal roofs* are typically made from sheet metals that can be soldered and are inherently durable in their natural state, requiring no protective finish, such as copper, lead-coated copper, or terne-coated stainless steel.
- *Contemporary architectural metal roofs* are typically made from sheet steel and aluminum, which have been treated with protective finishes. Thus, the metals commonly used in such roofs are painted steel, metallic-coated steel, and aluminum.

Traditional metal roofs have a long history, because they originated in an era when building construction relied entirely on manual fabrication and assembly. Although adapted to modern industrialized modes of construction, traditional metal roofs still rely to some extent on hand-detailed artisanry. That is why traditional metal roofs are also referred to as *custom metal roofs* and are the only metal roofs that can be used on complex roof geometries, including domes and cupolas.

Contemporary metal roofs are manufacturer specific, with hardly any custom-made components. The introduction of industrialized methods of metal forming and the discovery of durable paints and metallic coatings have made contemporary metal roofs an economical alternative to the traditional copper or lead-coated copper roofs. In fact, the durability and colorfastness of paints and coatings are responsible for the acceptance of sheet steel and aluminum as roofing material.

The discussion provided here is brief and applies to contemporary architectural metal roofs. For additional details, the reader should refer to a text that covers metal roofs in greater detail.

34.10 CONTEMPORARY ARCHITECTURAL METAL ROOFS

As stated earlier, architectural metal roofs require a deck and an underlayment. The deck can be any one of the deck types used in low-slope roof applications, such as concrete, steel, plywood, or oriented strandboard. In commercial buildings, in which steel or concrete decks are common, a typical metal roof assembly consists of the structural deck, one or two layers of insulation, a layer of plywood (or OSB), an underlayment, and the metal roof, Figure 34.39.

In this assembly, plywood (or OSB) works as a nail base to which the metal panels are fastened. The underlayment provides the secondary waterproofing and is generally one layer of No. 30 asphalt-saturated organic felt. In some applications, however, the nail base may be omitted, and the metal panels may be fastened to the deck through the insulation.

An ice dam protection membrane is also needed, as in other steep roofs. The recommendation for an ice dam protection membrane is the same as for other steep roofs. In areas with high snow loads, an ice dam protection membrane should be installed over the entire roof. Additionally, continuous ventilation under the plywood nail base should be provided, and the roof should be designed as a cold roof.

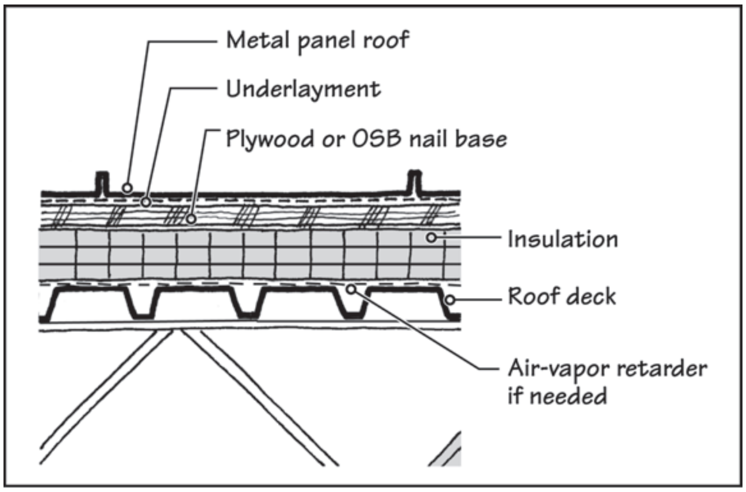


FIGURE 34.39 Typical anatomy of a metal panel roof.

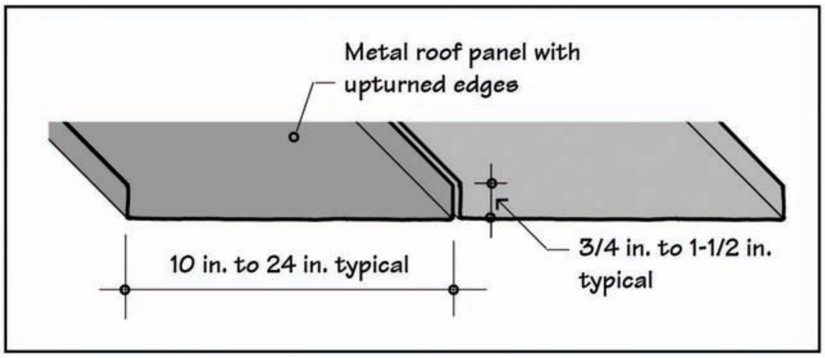

Metal roof panel with upturned edges
10 in. to 24 in. typical
3/4 in. to 1-1/2 in. typical

FIGURE 34.40 Typical metal panel roof profile.

FABRICATION OF CONTEMPORARY ARCHITECTURAL METAL ROOF PANELS

One of the several contemporary architectural metal roofs is the standing seam type, in which each panel has two upturned legs, one at each longitudinal edge of the panel. The upturn is generally $\frac{3}{4}$ in. to $1\frac{1}{2}$ in. high. A larger upturn is needed where rainfall intensity is high. The width of the panel varies from 10 in. to 24 in., Figure 34.40. The upturned edges of adjacent panels meet to form a seam, which can be waterproofed in several ways.

In addition to being shop fabricated, panels can be fabricated to the required profile at the construction site from a coil of (prefinished) sheet metal, Figure 34.41. This means that panels of almost any length can be used. The longer the panel, the smaller is the number of transverse seams.

In many cases, only one length of panel on each side of a sloping roof is needed, completely precluding the use of transverse seams. In such a case, there is only one joint between the two panels from the two opposite slopes of the roof—at the ridge. The length of a panel is limited by its handleability. Panels 100 ft in length are not uncommon.

Site fabrication of panels reduces the cost of transporting long panels from the factory to the site. In tall buildings, the panel-fabricating equipment is generally placed on the flat portion of the roof, which avoids the need to lift panels from the ground to the roof.

ANCHORING THE PANELS

The panels are fastened to the substrate by metal cleats, whose design varies from manufacturer to manufacturer. One such fastening method is shown in Figure 34.42. The center-to-center distance between cleats is a function of the wind uplift on the roof and may vary from 12 in. (or less) to 5 ft. The cleat shown is of a *fixed type* that does not allow any movement in panels. Generally, if panels are longer than 40 ft, *expansion cleats* are required. Expansion cleats allow the panels to move—an important requirement for long panels.

After the panels have been fastened, each seam is covered with a snap-on cover piece, Figure 34.43. The snap-on cover piece has a factory-applied sealant throughout the length of the cover piece, which squeezes over and around the panel seams, providing additional waterproofing, Figure 34.44.

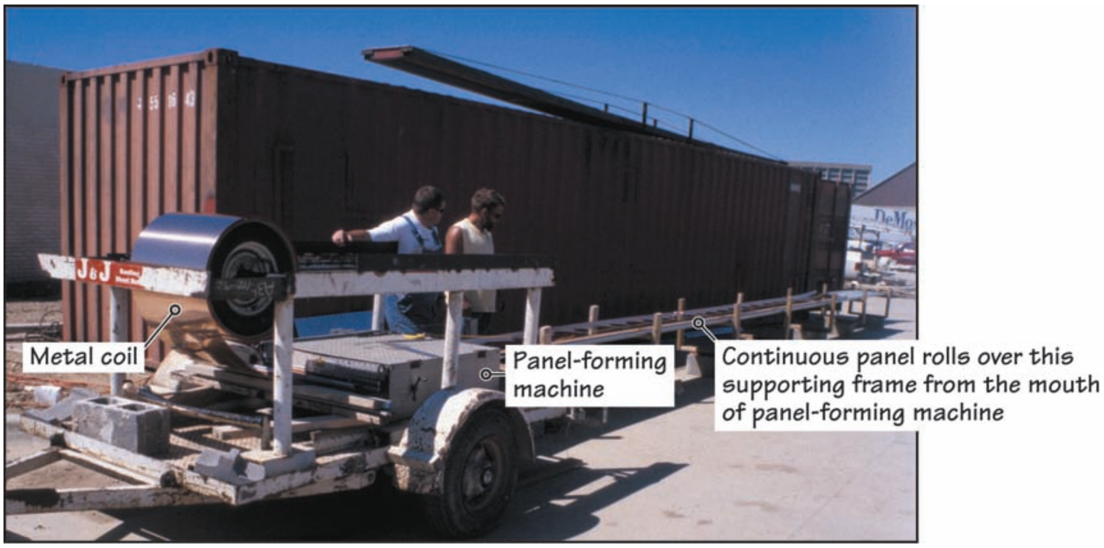

Metal coil
Panel-forming machine
Continuous panel rolls over this supporting frame from the mouth of panel-forming machine

FIGURE 34.41 For some projects (particularly those requiring long panels), architectural metal roof panels are fabricated at the construction site from a sheet-metal roll using a simple panel-forming machine. Panel length is restricted only by the handling capability. Large lengths are particularly difficult to handle on a windy day.

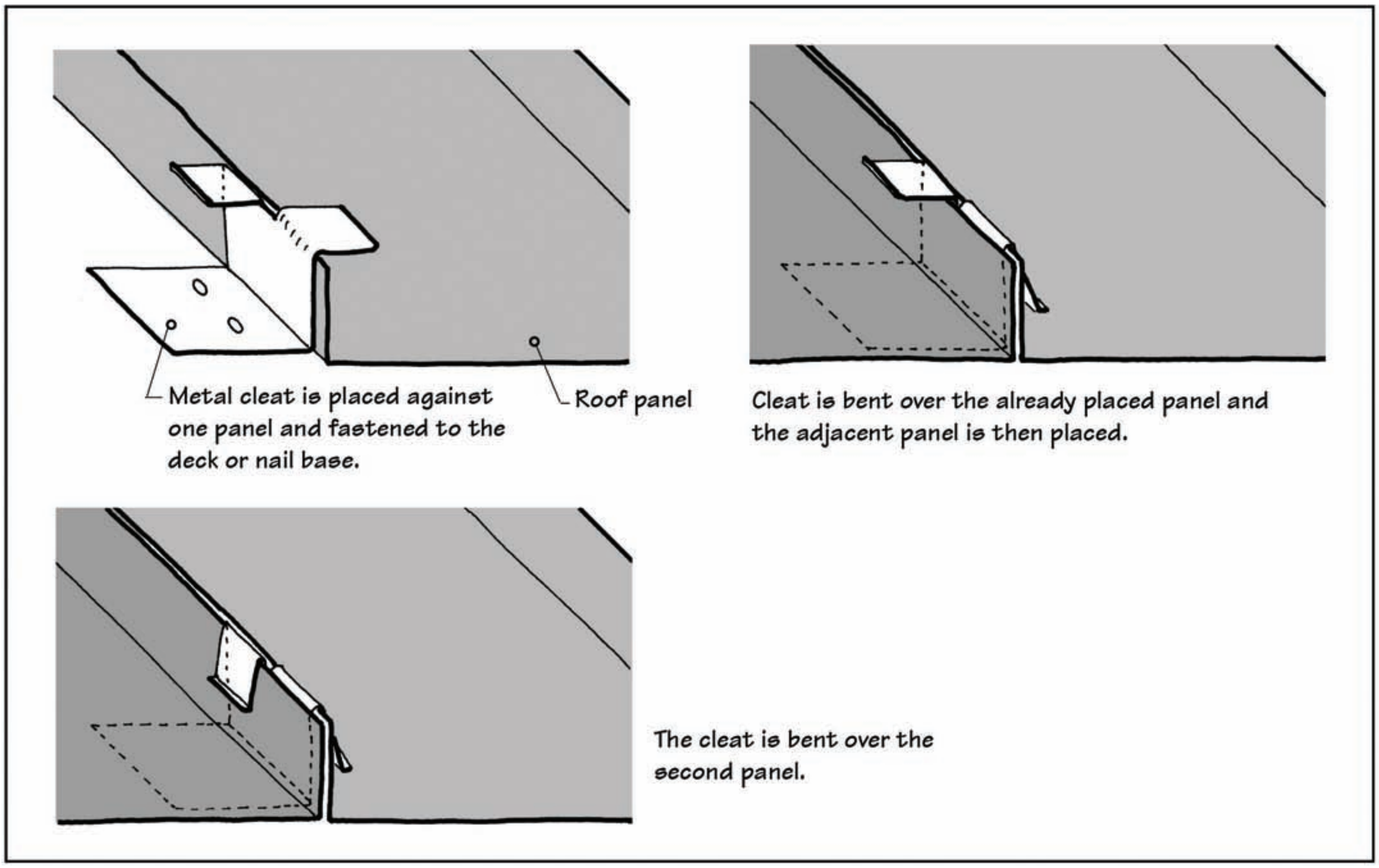

Metal cleat is placed against one panel and fastened to the deck or nail base.
Roof panel
Cleat is bent over the already placed panel and the adjacent panel is then placed.
The cleat is bent over the second panel.

FIGURE 34.42 Details of the anchorage of metal panels to a roof deck (or nail base) using sheet metal cleats.

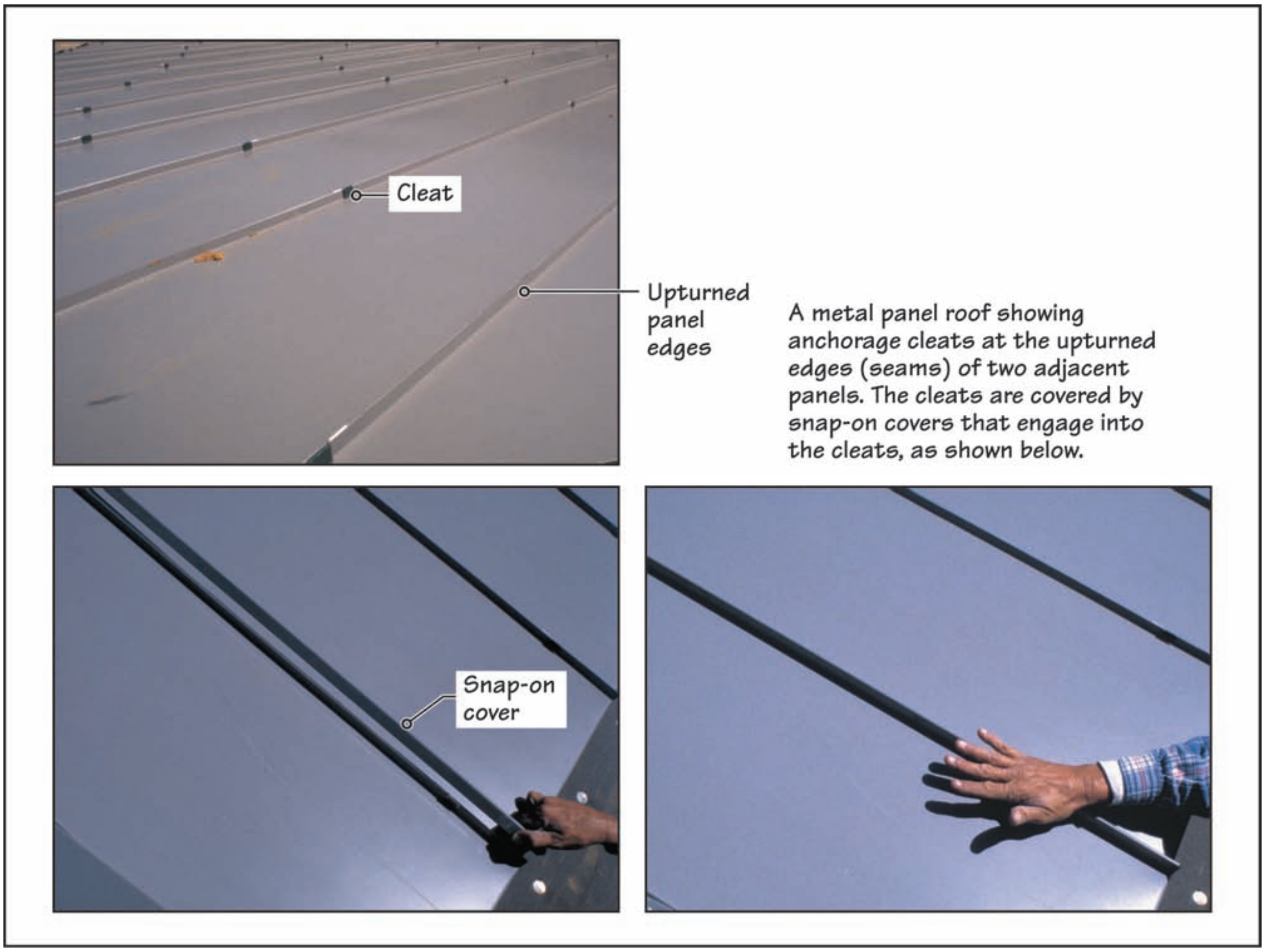

Cleat
Upturned panel edges
A metal panel roof showing anchorage cleats at the upturned edges (seams) of two adjacent panels. The cleats are covered by snap-on covers that engage into the cleats, as shown below.
Snap-on cover

FIGURE 34.43 Installation of snap-on cover pieces over panel seams.

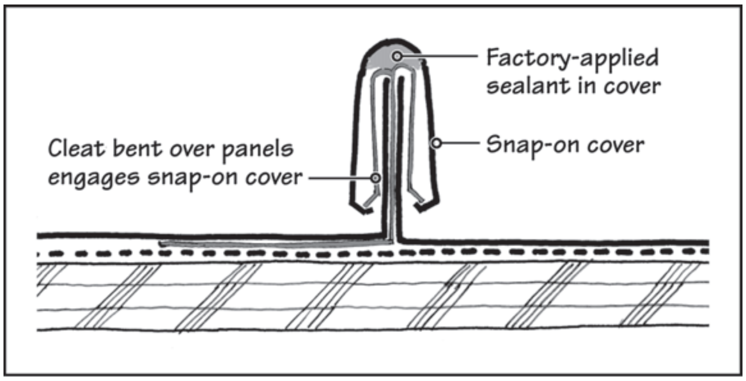

Factory-applied sealant in cover
Cleat bent over panels engages snap-on cover
Snap-on cover

FIGURE 34.44 Section through a seam showing the cleat and the snap-on cover.

RIDGE AND EAVE DETAILS

A typical ridge detail, which consists of a continuous Z-shaped sheet-metal closure set in sealant and soldered to the underlying metal panels, is shown in Figure 34.45. A preformed ridge cap engages into the closure. An ice dam protection membrane is adhered over the ridge directly below the roof panels. Figure 34.46 shows a typical eave detail. Note that the flat portion of the roof panels is turned over the eave flashing.

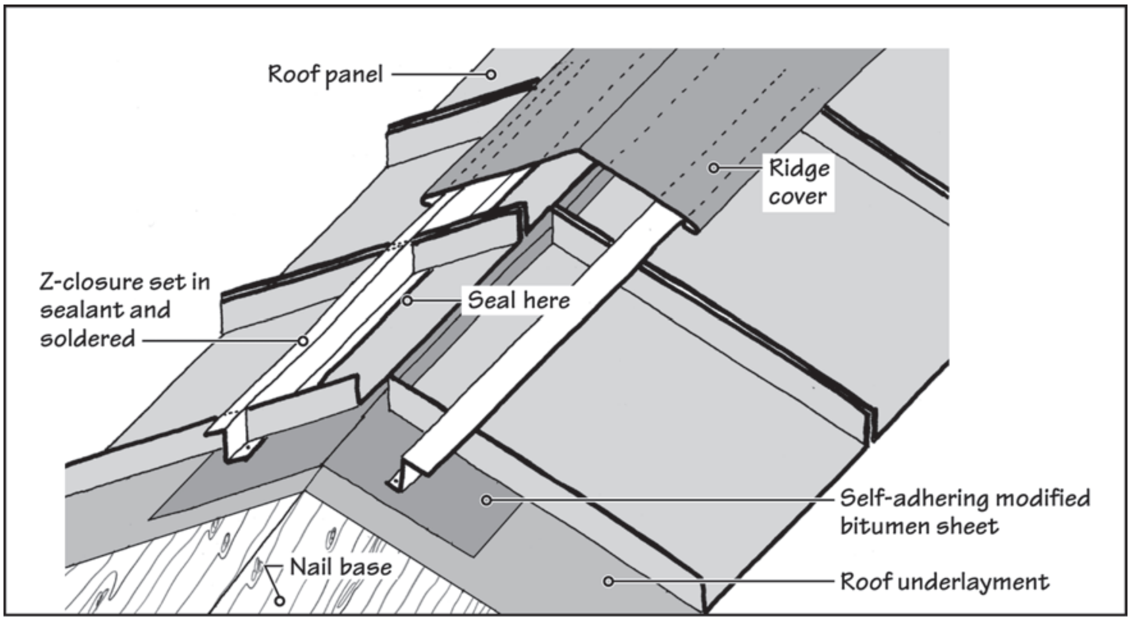

Roof panel
Ridge cover
Z-closure set in sealant and soldered
Seal here
Self-adhering modified bitumen sheet
Nail base
Roof underlayment

FIGURE 34.45 A typical ridge detail.

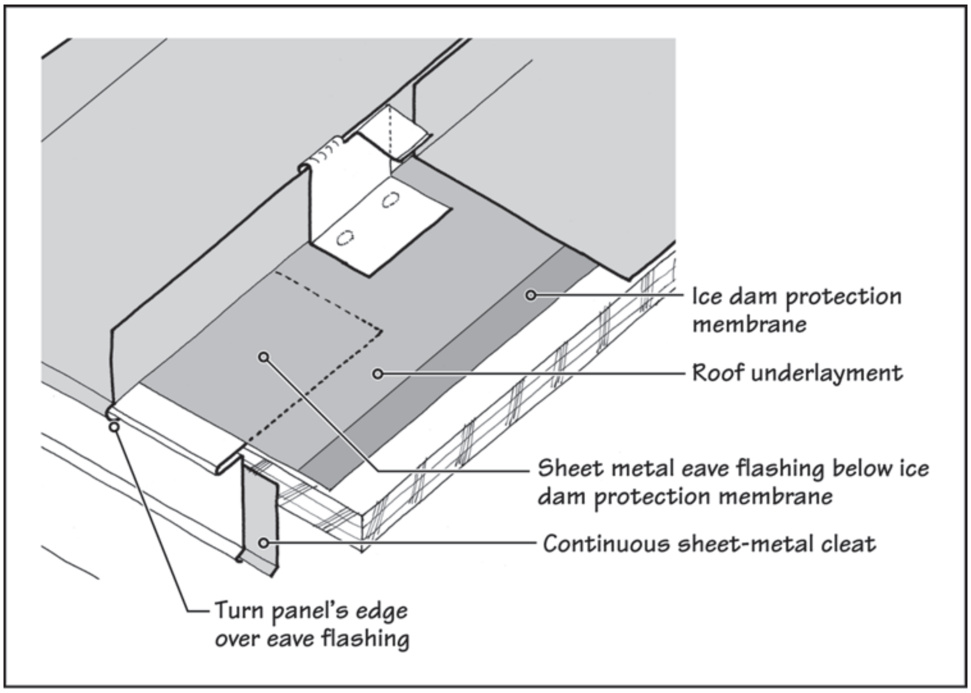

Ice dam protection membrane
Roof underlayment
Sheet metal eave flashing below ice dam protection membrane
Continuous sheet-metal cleat
Turn panel's edge over eave flashing

FIGURE 34.46 A typical eave detail.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

18. Clay and concrete tiles are generally laid in
- **a.** single coverage with a 5-in overlap between the top and bottom shingles.
- **b.** double coverage with a 2-in. overlap between the top and bottom shingles.
- **c.** double coverage with a 2-in. headlap between the top and bottom shingles.
- **d.** triple coverage with no headlap.
- **e.** none of the above.

19. A roof tile profile that resembles a barrel is generally referred to as a
- **a.** *barrel tile*.
- **b.** *mission tile*.
- **c.** *semicircular tile*.
- **d.** all of the above.

20. Because a clay or concrete tile roof is more durable, the requirement for roof underlayment in a concrete or clay tile roof is less stringent than that in an asphalt shingle roof.
- **a.** True
- **b.** False

21. Everything else being the same, which of the following clay or concrete tile roofs gives the best performance?
- **a.** Tiles laid over a two-way batten system
- **b.** Tiles laid over a one-way batten system
- **c.** Tiles without any batten system

22. The batten system in a clay or concrete tile roof is installed
- **a.** between the roof deck and the roof underlayment.
- **b.** between the deck and the clay (or concrete) tiles.
- **c.** between the roof underlayment and the clay (or concrete) tiles.
- **d.** none of the above.

23. The primary purpose of a batten system in a clay (or concrete) tile roof is to
- **a.** provide a nail base for tiles.
- **b.** provide a cushion to the tiles.
- **c.** provide a drainage layer under the tiles.
- **d.** none of the above.

24. Mission tile roofs require a treated-wood nailer under each row of tiles. The nailer is generally
- **a.** 2 × 2 lumber.
- **b.** 2 × 3 lumber.
- **c.** 2 × 4 lumber.
- **d.** (a) or (b).
- **e.** (b) or (c).

25. An architectural metal roof serves both as roof deck and roof cover.
- **a.** True
- **b.** False

26. An architectural metal roof can be used as a low-slope or steep roof.
- **a.** True
- **b.** False

27. In a standing-seam metal roof, the roof panels are
- **a.** shop formed and site finished.
- **b.** shop formed and shop finished.
- **c.** site formed from a prefinished sheet-metal roll.
- **d.** any one of the above.

REVIEW QUESTIONS

1. Using a sketch, explain the essential components of a steep roof.
2. What is a steep roof underlayment? With the help of a sketch, explain the underlayment requirements for an asphalt shingle roof.
3. Explain what an ice dam protection membrane is and the material it is made of. With the help of a sketch, explain its use on an asphalt shingle roof.
4. Sketch a typical three-tab asphalt shingle, showing the adhesive lines and their purpose.
5. Explain the pros and cons of using an open valley, a closed-cut valley, and a woven valley in an asphalt shingle roof.
6. Explain what step flashing is, the material it is made of, and where it is commonly used.
7. Using a sketch, explain the layout of clay or concrete tiles using a treated-wood crossbatten system.
8. Using a sketch, explain the components of an architectural metal roof.

CHAPTER 35

Stairs

CHAPTER OUTLINE

35.1 STAIR FUNDAMENTALS
35.2 WOOD STAIRS
35.3 STEEL STAIRS
35.4 CONCRETE STAIRS
35.5 FREESTANDING CANTILEVERED STAIRS

A stair, defined as a series of ascending (or descending) steps, is an important element that allows occupants to move vertically in a building. Architectural historians claim that the stair remained a purely functional element (without artistic overtones) until the end of the fifteenth century. The beginning of the sixteenth century, inspired by Leonardo da Vinci's sketches, however, "signaled a new era of expression for the staircase" [Ref. 35.1]. From then on, the staircase played an increasingly important visual role, often becoming a sculptural feature in a space, an imperial entrance to a public building or a significant facade element.

The birth of the elevator—and, subsequently, the escalator—reduced the importance of the stair. More recently, the requirement to make buildings accessible to persons with disabilities further eroded its significance.

Because a stair cannot be used by people in a wheelchair, it is no longer a mandatory feature of an entrance lobby. (Increasingly, entrance lobbies in contemporary public buildings are designed without a stair.) Consequently, stairs are reverting to their purely functional role—fulfilling the requirement as exit stair or standby vertical circulation in the event of electrical outage or mechanical interruption.

However, despite the stair's decreasing significance, in many contemporary buildings the rhythm and repetitive features of a stair have been transformed into an important aesthetic component of the interior space, as shown by the images in Figure 35.1. This chapter begins with a general introduction to stairs, followed by the details of construction of simple wood, steel, and concrete stairs.

35.1 STAIR FUNDAMENTALS

Because a stair provides vertical transportation, it is part of the means-of-egress (exit) system of a building. It is also a relatively hazardous element because injuries due to falls from stairs are not uncommon. For this reason, stair design is stringently controlled by building codes.

TREAD, RISER, AND NOSING

There are two main components of a stair: *treads* and *risers*. A tread is the horizontal surface on which one walks. The riser is the vertical component that separates one tread from

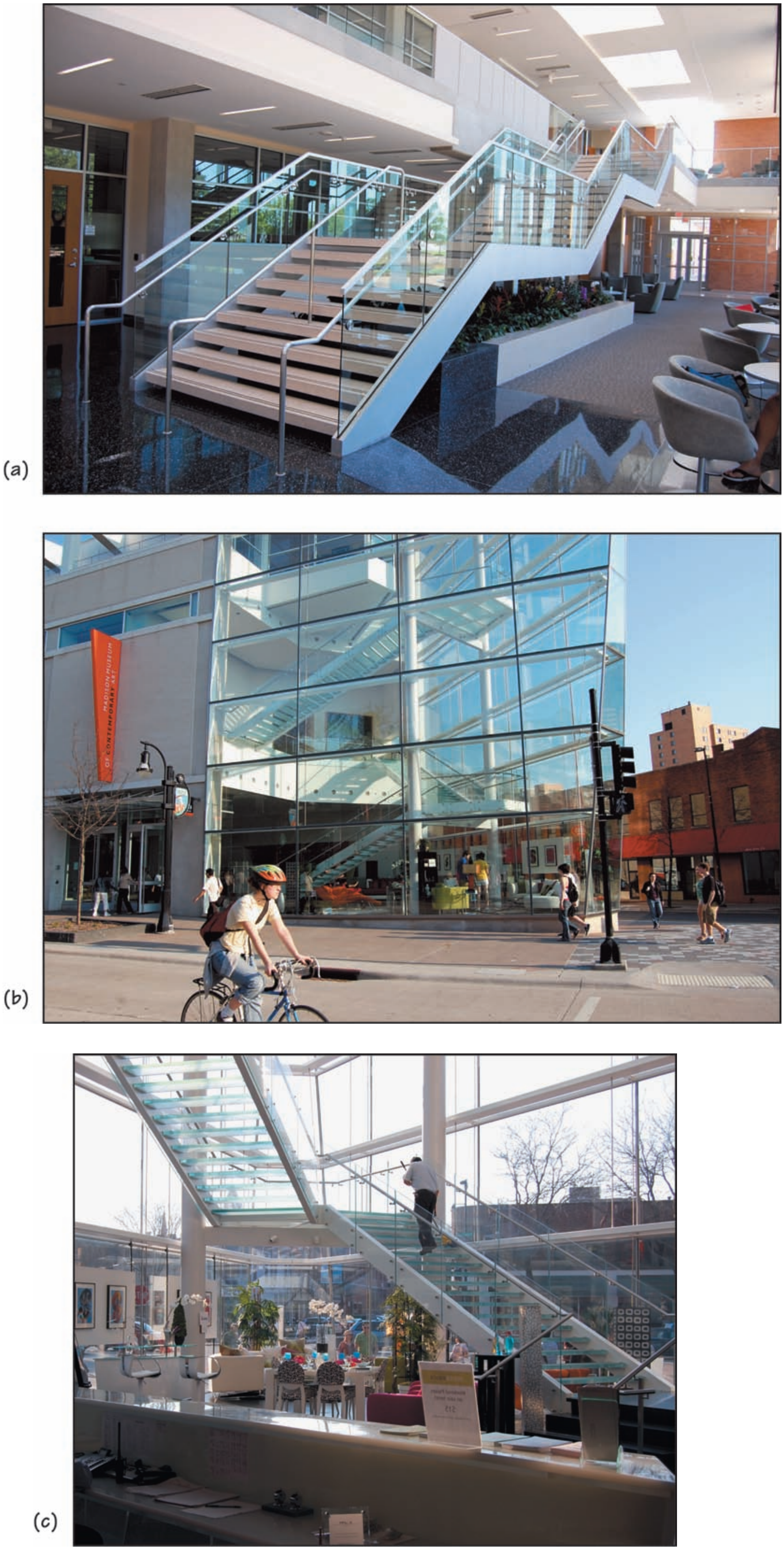


FIGURE 35.1 Images showing the aesthetic potential of stairs; see also Figure 35.20. **(a)** An entrance lobby stair with structural-steel beams (stringers) and concrete-filled sheet-steel tread pans (see Figure 35.13). **(b)** A highly transparent glass wall showcasing the stair in the Madison Museum of Contemporary Art, Madison, Wisconsin. **(c)** Stair in the entrance lobby of the Madison Museum of Contemporary Art, Madison, Wisconsin with structural-steel beams (stringers) and glass treads. Architect: Cesar Pelli and Associates.

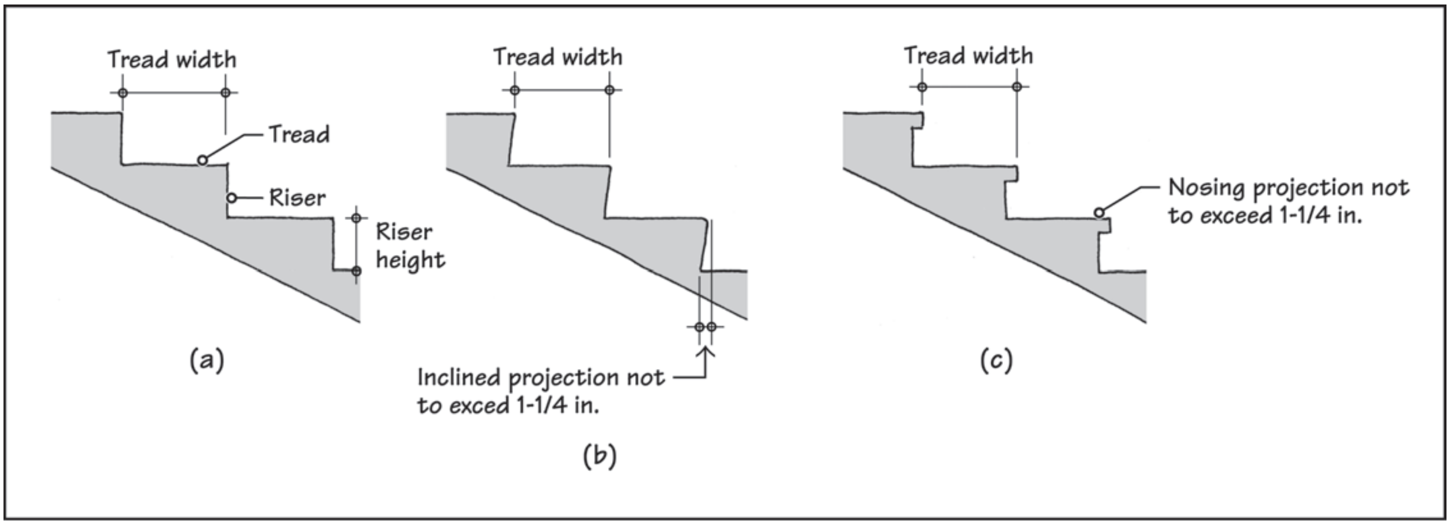

Tread width
Tread
Riser
Riser height
(a)
Tread width
Inclined projection not to exced 1-1/4 in.
(b)
Tread width
Nosing projection not to exceed 1-1/4 in.
(c)

FIGURE 35.2 Tread, riser, and nosing configurations in a stair.

another. Generally, a stair has several treads and risers. For the sake of safety, the dimensions of treads and risers must be uniform in a stair. Building codes allow a small dimensional variation because perfect uniformity is unachievable.

In walking on a horizontal or an inclined surface, an average person can comfortably traverse a distance of 24 in. to 25 in. in one step. Therefore, a rule of thumb generally used in proportioning the treads and risers of a stair is

$$2\ (\text{riser height}) + \text{tread width} = 24\text{ in. to }25\text{ in.}$$

Thus, if the risers in a stair are each 5 in. high, the tread width should lie between 14 in. and 15 in. The most commonly used dimensions for an interior public stair are 12-in. to 13-in. treads and 6-in. risers. Outdoor stairs generally have a smaller riser and hence a wider tread. Building codes generally require a riser height between 4 in. and 7 in. and a minimum tread width of 11 in.

In most stairs, the tread is a simple flat surface, and the riser is a solid vertical surface, Figure 35.2(a). Where space is limited, the effective tread width can be increased somewhat by inclining the risers, Figure 35.2(b), or by projecting the front edge of the tread beyond the riser, Figure 35.2(c). The front edge of a tread is referred to as the *nosing*.

When an inclined riser or a projected nosing is used, the code-required minimum width of a tread does not change. In other words, the width of a tread is considered the horizontal distance between the vertical planes of the foremost projections of adjacent treads, as shown in Figures 35.2(b) and (c).

The nosing of a tread is subjected to the maximum abrasion. In public stairs with heavy traffic, the treads should consist of a strong, dense material such as granite, high-strength concrete, or steel. Alternatively, a separate nosing (approximately $2\frac{1}{2}$ in. wide) consisting of an abrasion-resistant and skid-resistant material is epoxied or embedded into the tread.

Stairs can also be constructed without risers, referred to as *open-riser stairs*, Figure 35.3. Because of safety concerns, open-riser stairs are subject to more stringent code restrictions than stairs with solid risers. For example, open-riser stairs are generally not allowed as exit stairs. Additionally, the clear vertical distance between the treads of open-riser stairs cannot exceed 4 in.

NOTE

Treads and Risers of a Stair

The treads and risers of a stair must meet the following dimensional requirements:

Minimum tread width = 11 in.

Riser height = 4 in. to 7 in.

Residential Stair

Building codes are less restrictive for a stair within a dwelling unit:

Minimum tread width = 10 in.

Riser height = 4 in. to $7\frac{3}{4}$ in.

A 10-in. tread is allowed in a dwelling unit stair, provided that a nosing projection of $\frac{3}{4}$ in. to $1\frac{1}{4}$ in. is used. If a nosing projection is not used, an 11 in. minimum tread width is required.

Some local building codes may allow a riser height of greater than $7\frac{3}{4}$ in. for a residential basement stair.

STAIR SHAPES

The most commonly used stair shape is a U-shaped stair (in plan). It consists of two flights of stairs between floors with a midfloor landing (or simply a *midlanding* or *landing*), Figure 35.4. In addition to the U-shaped stair, some of the other commonly used stair shapes are as follows:

- *Straight-run stair* with one or two flights, Figure 35.5: A straight-run stair with more than two flights can be used, but this is uncommon.
- *L-shaped stair*, Figure 35.6(a): Where the space is limited, the landing of an L-shaped stair can be used for steps, yielding trapezoidal (pie-shaped) treads, referred to as *winders*, Figure 35.6(b). Stairs with winders are not as safe as those with rectangular treads, and their use in an exit stair is strictly controlled by building codes.

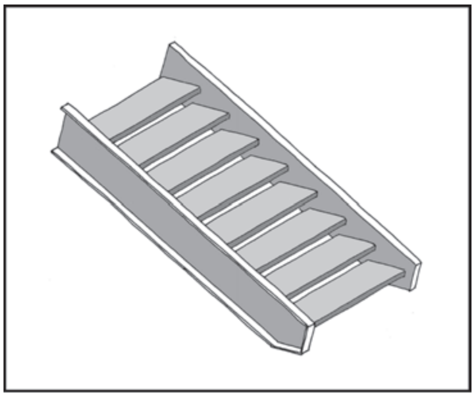


FIGURE 35.3 A stair with open risers.

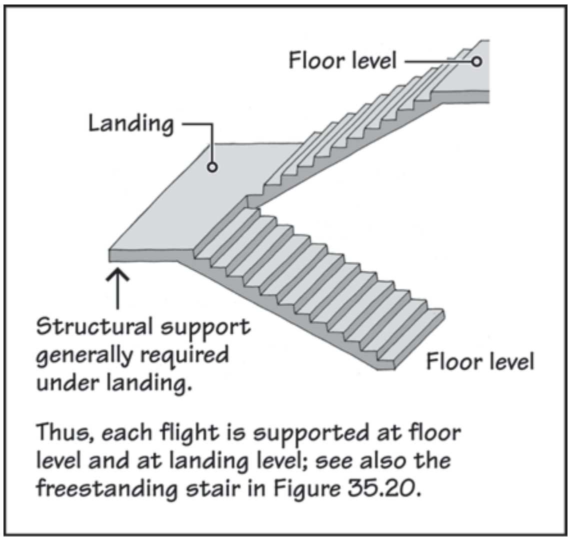

Floor level
Landing
Structural support generally required under landing.
Floor level
Thus, each flight is supported at floor level and at landing level; see also the freestanding stair in Figure 35.20.

FIGURE 35.4 A U-shaped stair.

- *Circular stair:* A circular stair may consist of all winders and can take many shapes. A spiral stair is a special type of circular stair in which the treads twist around a central column and are cantilevered from it, Figure 35.7. It is generally an open-riser stair. Again, building codes have several restrictions on the use of a spiral stair. A helical stair is a circular stair without a central supporting column (see Section 35.5).

OPEN AND CLOSED STAIRS

Stairs are also described as either open or closed. An open stair is exposed to the area below on one or more sides, whereas a closed stair is fully enclosed with a stair enclosure (stair shaft) and is usually accessed through a doorway.

WIDTH OF STAIR

The minimum width of a stair is determined by its purpose. When it is used as an exit stair, its width depends on the number of occupants it serves (occupant load) but is not less than 44 in. clear (between adjacent handrails) for an open exit stair or 48 in. for an enclosed exit stair. An exit stair for an occupant load of less than 50, or a stair within a dwelling unit, has a minimum width of 36 in.

HEADROOM

The headroom in a stair is the minimum clearance between a tread and a projection above, Figure 35.8. Building codes generally require the headroom to be a minimum of 80 in. at any point on the stair.

GUARD UNIT, HANDRAIL, BALUSTERS, AND NEWEL POST

The edge of a stair exposed to a change in height (i.e., not protected by the wall of the enclosure) must have a *guard unit* to protect against falling. The minimum height of a guard unit is 42 in., Figure 35.9(a). The clear distance of openings in a guard unit must not exceed 4 in.

The height of a handrail in a stair is generally required to lie between 34 in. and 38 in. The cross-sectional profile of a handrail is controlled by building codes to give it the required graspability.

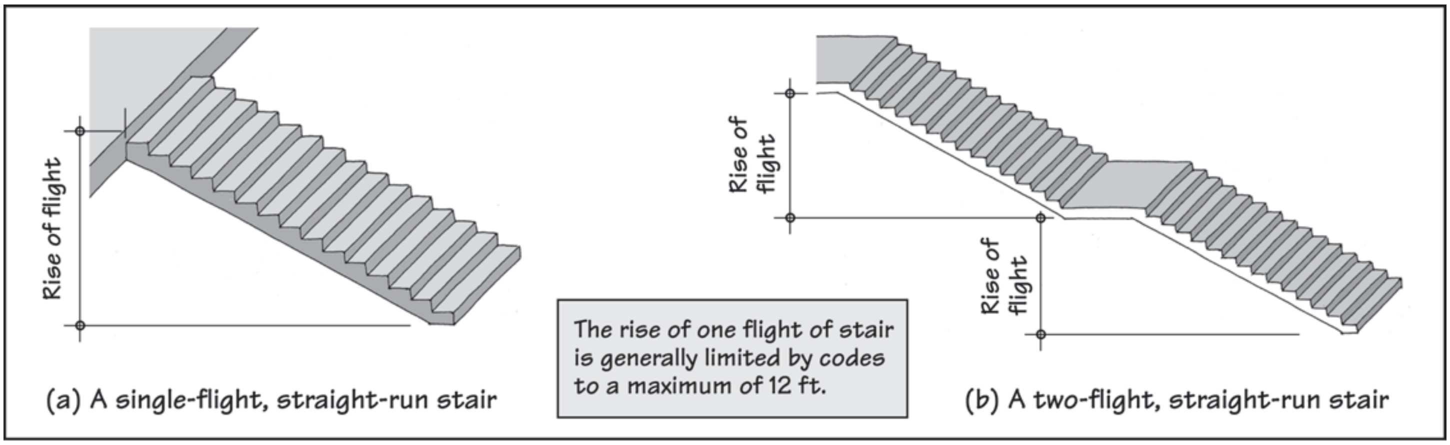

Rise of flight
(a) A single-flight, straight-run stair
The rise of one flight of stair is generally limited by codes to a maximum of 12 ft.
Rise of flight
Rise of flight
(b) A two-flight, straight-run stair

FIGURE 35.5 Straight-run stairs; see Figure 35.1(a).

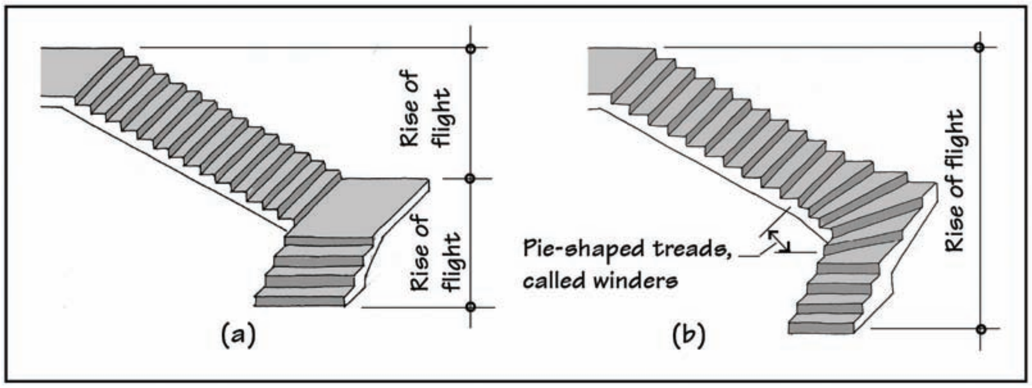
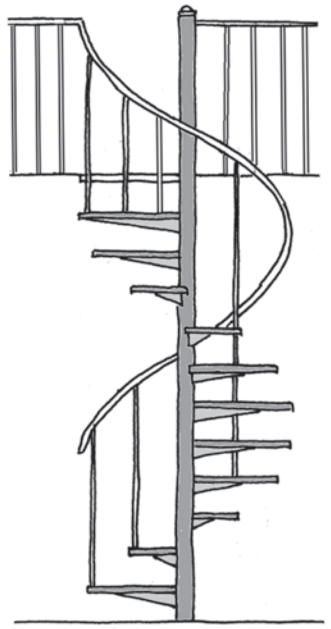
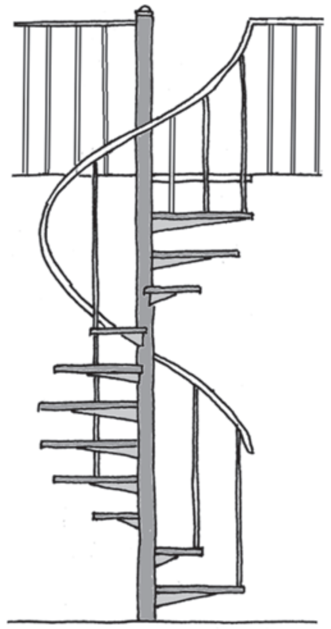

Rise of flight
Rise of flight
(a)
Pie-shaped treads, called winders
Rise of flight
(b)

FIGURE 35.6 L-shaped stairs **(a)** without winders and **(b)** with winders.



A spiral stair with a handrail on the left allows a right-hand grip on the handrail when walking down (preferred by some designers).



A spiral stair with a handrail on the right allows a right-hand grip on the handrail when walking up.

FIGURE 35.7 A spiral stair.

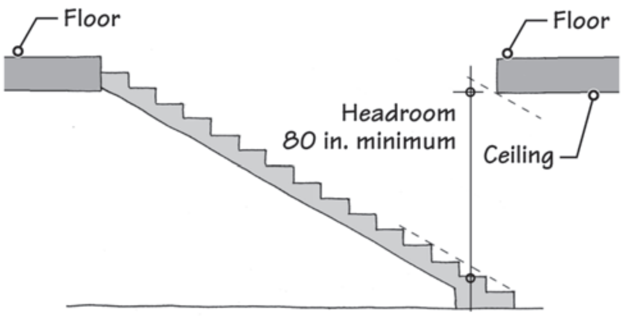


FIGURE 35.8 Headroom in a stair.

In some wood stairs, the first and/or the last vertical member of the guard unit (referred to as a *baluster*) is highlighted by using a more ornate design. Such a baluster is referred to as a *newel post*, Figure 35.9(b).

STAIR LAYOUT AND STAIR PLAN

In preparing a stair layout, we first determine the floor-to-floor height and then calculate the number of risers and treads. Assume that the floor-to-floor height in a building is 10 ft 8 in., that is, 128 in. Assume further that we would like the riser height to be approximately 6 in. Dividing 128 by 6 gives us the number of risers:

$$\text{Number of risers} = \frac{128}{6} = 21.3$$

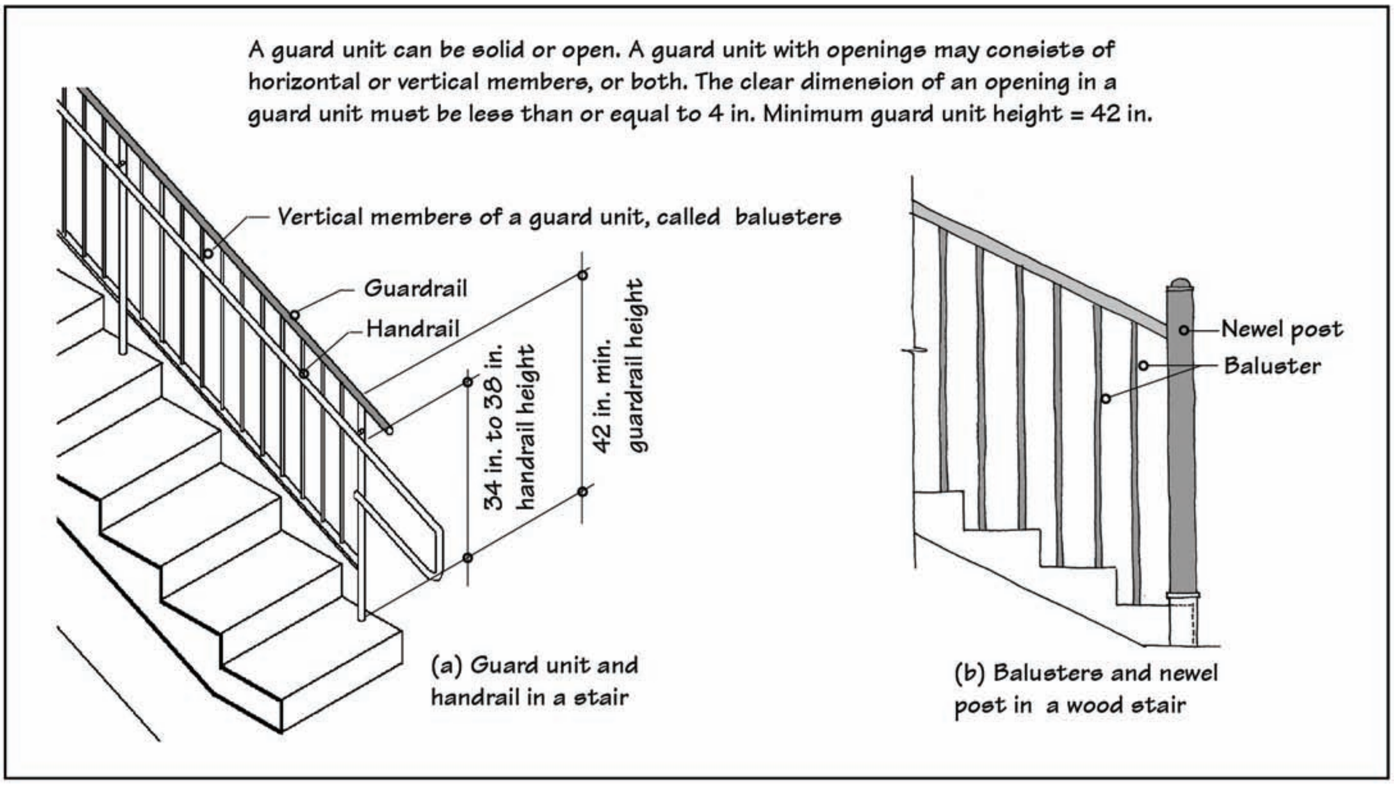

A guard unit can be solid or open. A guard unit with openings may consists of horizontal or vertical members, or both. The clear dimension of an opening in a guard unit must be less than or equal to 4 in. Minimum guard unit height = 42 in.
Vertical members of a guard unit, called balusters
Guardrail
Handrail
34 in. to 38 in. handrail height
42 in. min. guardrail height
(a) Guard unit and handrail in a stair
Newel post
Baluster
(b) Balusters and newel post in a wood stair

FIGURE 35.9 Guard unit, handrail, balusters, and newel post.

Because the number of risers must be a whole number, assume 21 risers. Dividing 128 in. by 21 gives the exact riser height, 6.1 in. From the tread-riser relationship given earlier, the tread width is

$$24\text{ (or 25)} - 2\,(6.1) = 11.8\text{ in. to }12.8\text{ in.}$$

We will use a tread width of 12.0 in. Assume further that a U-shaped stair is desired and the width of the stair is 4 ft. By code, the minimum width of the landing must be the same as the width of the stair, that is, 4 ft. With these data, a plan of the stair can be drawn, as shown in Figure 35.10.

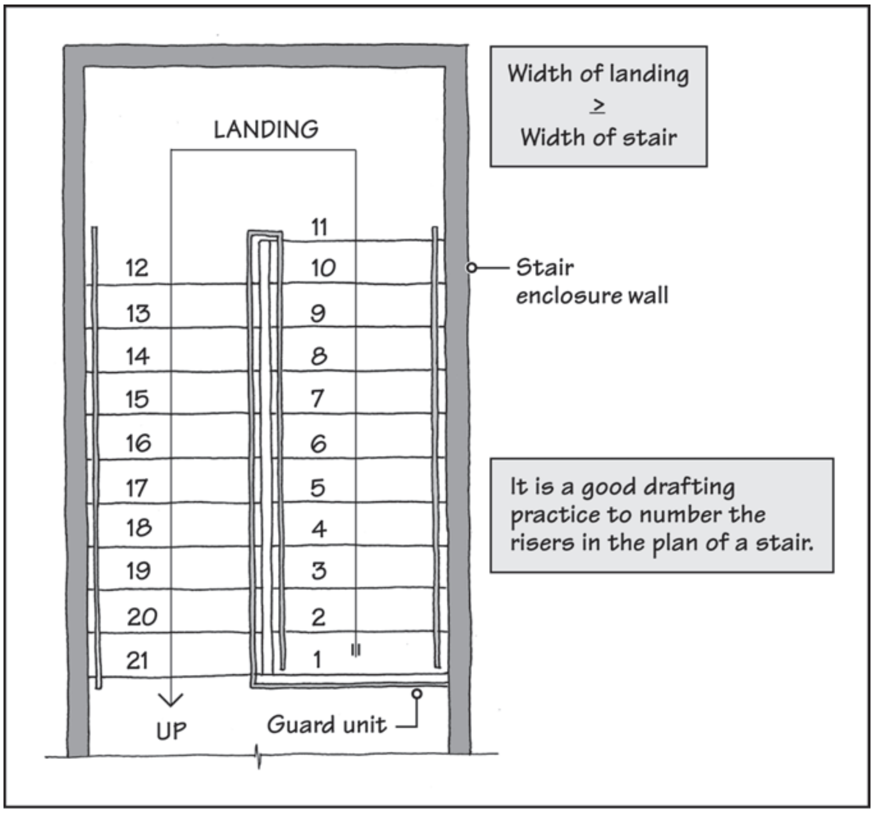

Width of landing ≥ Width of stair
LANDING
11
12
10
13
9
14
8
15
7
16
6
17
5
18
4
19
3
20
2
21
1
Stair enclosure wall
It is a good drafting practice to number the risers in the plan of a stair.
UP
Guard unit

FIGURE 35.10 Plan of a U-shaped stair (at the second-floor level) that extends only from the first floor to the second floor.

EXPAND YOUR KNOWLEDGE

Summary of Stair-Design Criteria

1. Tread depth and riser height must be dimensionally uniform throughout.
2. Minimum tread width = 11 in. Riser height = 4 in. to 7 in. (See Section 35.1 for exceptions for residential stairs.)
3. Nosing projection ≤$1\frac{1}{4}$ in.
4. Stair width = function of the occupant load, but not less than 48 in. for an enclosed exit stair, 44 in. for an open exit stair, or 36 in. for a stair serving an occupant load of less than 50 or a residential stair.
5. Width of landing ≥stair width.
6. Rise of one flight ≤12 ft.
7. Headroom ≥80 in.
8. Use of winders is restricted.
9. Height of guardrail = 42 in. minimum. Height of handrail = 34 in. to 38 in.
10. Handgrip portion of the handrail must have a circular cross section between $1\frac{1}{4}$ in. and $2\frac{5}{8}$ in. Noncircular profiles must provide equivalent graspability.

STAIR-DRAWING CONVENTIONS

There are standard conventions for how stairs are shown in building plans. Figure 35.10 is the plan at the second-floor level of a U-shaped stair that extends from the first to the second floor only. The plan of the same stair at the first-floor level is shown in Figure 35.11(a). If the same stair were to extend over several floors, then the plan of the stair at a typical floor would generally be drawn as shown in Figure 35.11(b).

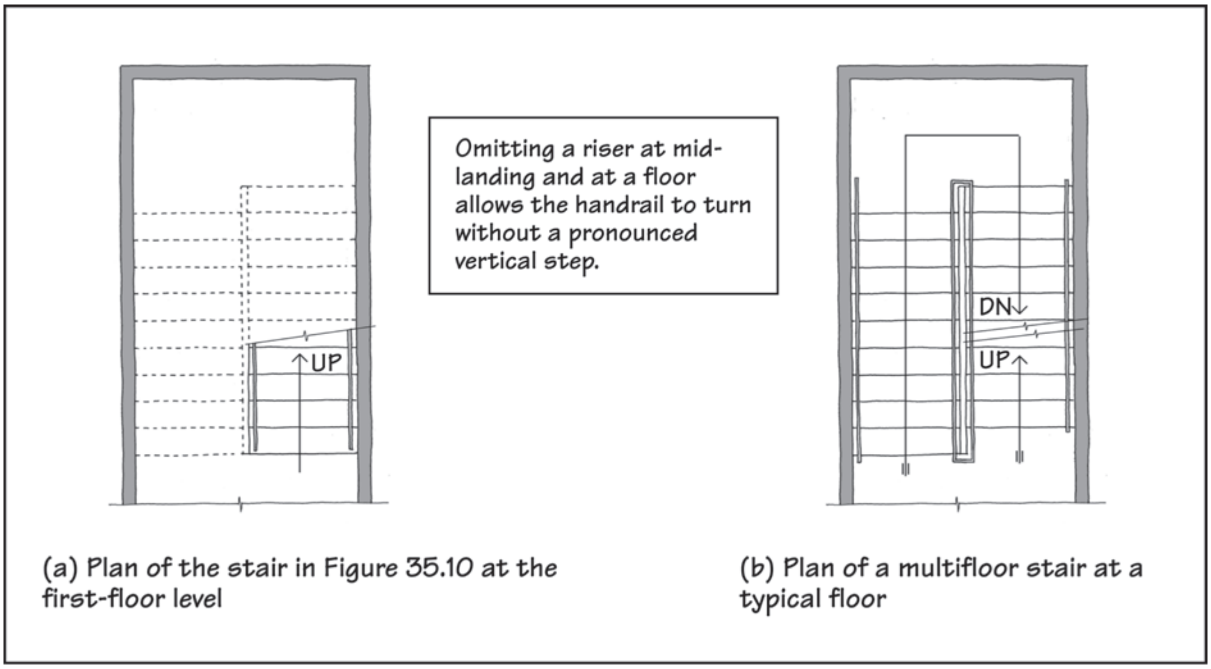
FIRE-RATED STAIR (SHAFT) ENCLOSURE

Because most stairs in a building are used as exit stairs, they need to be enclosed by vertical enclosures (also referred to as *shafts* or *shaft enclosures*). Generally, a shaft enclosure is required to be 1-h rated for a building up to four stories tall and 2-h rated for a building with five stories or more. Shafts are not required for individual single-family dwellings (up to four stories tall).

Building codes also contain several other exceptions to the requirement of shaft enclosures. For example, shafts are not required if the stair connects only two floors and is not used as an exit stair.

35.2 WOOD STAIRS

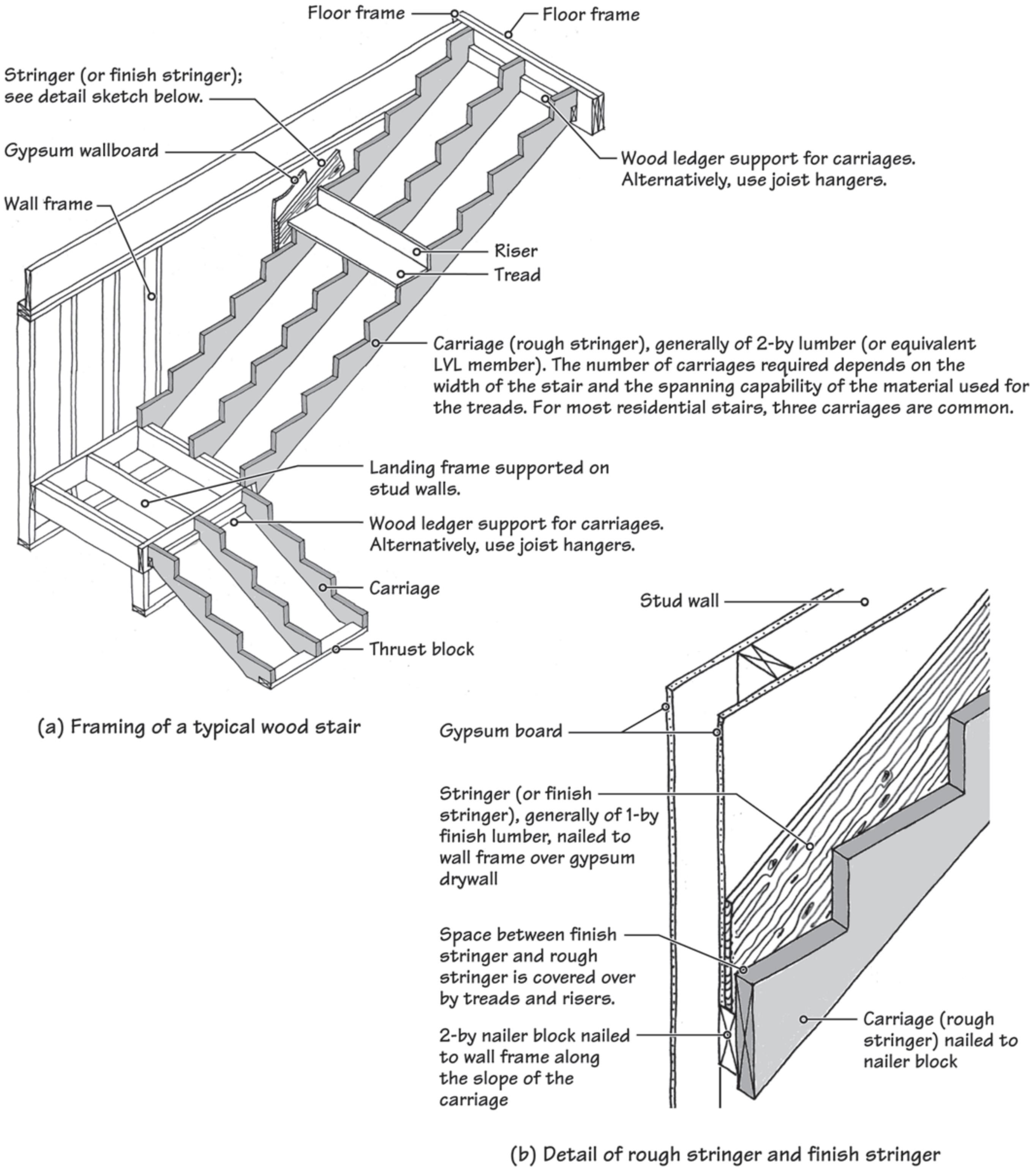
The most important parts of a wood stair are the *carriages* (also called *rough stringers*). Carriages are the structural elements of a stair (inclined beams) and are specially cut to support the treads. Figure 35.12 shows a commonly used method of framing a wood stair.


UP
Omitting a riser at mid-landing and at a floor allows the handrail to turn without a pronounced vertical step.
DN
UP

(a) Plan of the stair in Figure 35.10 at the first-floor level

(b) Plan of a multifloor stair at a typical floor

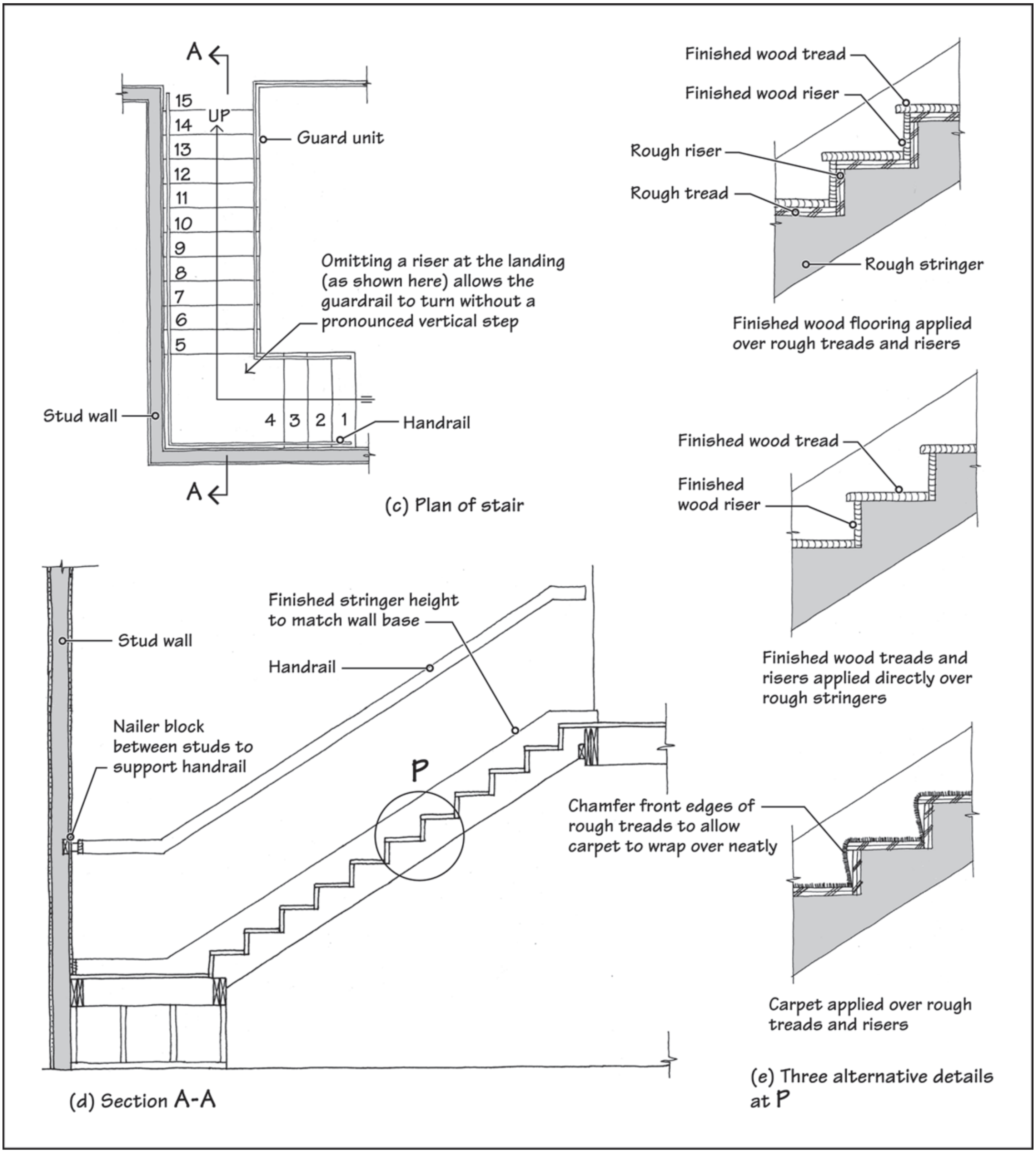
FIGURE 35.11 Stair plans at different levels.


Floor frame
Floor frame
Stringer (or finish stringer); see detail sketch below.
Gypsum wallboard
Wall frame
Wood ledger support for carriages. Alternatively, use joist hangers.
Riser
Tread
Carriage (rough stringer), generally of 2-by lumber (or equivalent LVL member). The number of carriages required depends on the width of the stair and the spanning capability of the material used for the treads. For most residential stairs, three carriages are common.
Landing frame supported on stud walls.
Wood ledger support for carriages. Alternatively, use joist hangers.
Carriage
Thrust block
Stud wall
Gypsum board
Stringer (or finish stringer), generally of 1-by finish lumber, nailed to wall frame over gypsum drywall
Space between finish stringer and rough stringer is covered over by treads and risers.
2-by nailer block nailed to wall frame along the slope of the carriage
Carriage (rough stringer) nailed to nailer block

(a) Framing of a typical wood stair

(b) Detail of rough stringer and finish stringer

FIGURE 35.12 A commonly used framing system for a wood stair.


A
15
14
UP
13
12
11
10
9
8
7
6
5
4
3
2
1
Guard unit
Omitting a riser at the landing (as shown here) allows the guardrail to turn without a pronounced vertical step
Stud wall
Handrail
A
Finished wood tread
Finished wood riser
Rough riser
Rough tread
Rough stringer
Finished wood flooring applied over rough treads and risers
Finished wood tread
Finished wood riser
Finished wood treads and risers applied directly over rough stringers
Finished stringer height to match wall base
Stud wall
Handrail
Nailer block between studs to support handrail
P
Chamfer front edges of rough treads to allow carpet to wrap over neatly
Carpet applied over rough treads and risers

(c) Plan of stair

(d) Section A-A

(e) Three alternative details at P

FIGURE 35.12 (*Continued*) A commonly used framing system for a wood stair.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. An approximate formula generally used in determining the tread dimension (T) and riser dimension (R) in a stair is
- **a.** 2T + R = 24 in. to 25 in.
- **b.** 2T + 2R = 24 in. to 25 in.
- **c.** 2R + T = 24 in. to 25 in.
- **d.** R + T = 24 in. to 25 in.
- **e.** none of the above.

2. The minimum tread width required by building codes for a nonresidential stair is
- **a.** 11.0 in.
- **b.** 11.5 in.
- **c.** 12.0 in.
- **d.** 12.5 in.
- **e.** 13.0 in.

3. The minimum riser height required by building codes for a nonresidential stair is
- **a.** 6.0 in.
- **b.** 5.5 in.
- **c.** 5.0 in.
- **d.** 4.5 in.
- **e.** 4.0 in.

4. The maximum nosing projection allowed for a stair is
- **a.** 3.0 in.
- **b.** $2\frac{1}{2}$ in.
- **c.** 2 in.
- **d.** $1\frac{1}{2}$ in.
- **e.** $1\frac{1}{4}$ in.

5. A riser must be vertical. It cannot be inclined.
- **a.** True
- **b.** False

6. A U-shaped stair has been provided between the first floor and the second floor of a building with a midlanding. This stair has
- **a.** one flight.
- **b.** two flights.
- **c.** three flights.
- **d.** four flights.

7. The rise of one flight of stair is generally limited by building codes to
- **a.** 7 ft.
- **b.** 8 ft.
- **c.** 10 ft.
- **d.** 12 ft.

8. Given a multistory building with a floor-to-floor height of 10 ft and an optimal riser height of 7 in., how many treads would you use for a U-shaped stair with a midlanding between floors? (The landing is not counted as a tread.)
- **a.** 15
- **b.** 16
- **c.** 17
- **d.** 18
- **e.** None of the above

9. A handrail and a guardrail in a stair are synonymous.
- **a.** True
- **b.** False

10. The minimum height of a guardrail in a stair is
- **a.** 34 in.
- **b.** 36 in.
- **c.** 38 in.
- **d.** 40 in.
- **e.** none of the above.

11. A stair constructed without risers is generally called a
- **a.** no-riser stair.
- **b.** closed-riser stair.
- **c.** open-riser stair.
- **d.** hollow stair.

12. A stair with treads cantilevered from a central column is a
- **a.** circular stair.
- **b.** U-shaped stair.
- **c.** L-shaped stair.
- **d.** spiral stair.
- **e.** helical stair.

13. The minimum width of a stair in a dwelling unit is
- **a.** 2 ft 6 in.
- **b.** 3 ft.
- **c.** 3 ft 6 in.
- **d.** 4 ft.
- **e.** none of the above.

PREFABRICATED WOOD STAIRS

There are several manufacturers who supply prefabricated wood stairs per the architect's design. Prefabricated wood stairs are usually transported in a knocked-down (KD) version, where each part is uniquely numbered for assembly on site. They are commonly used for more ornate stairs requiring detailed millwork and craft, which are not usually possible at the site.

35.3 STEEL STAIRS

Stairs in public buildings are generally constructed of steel or concrete. Because steel stairs can be shop fabricated and brought to the site ready for installation, they are far more commonly used than concrete stairs. Another reason for the lack of use of concrete stairs is that their formwork is complicated and expensive.

Prefabricated steel stairs are used in all types of public buildings, that is, steel- and concrete-frame buildings and load-bearing masonry buildings. They are particularly popular for exit stairs.

A typical prefabricated flight of a steel stair consists of two stringer beams (stringers) to which tread-riser units made of sheet steel are welded, Figure 35.13.

The tread pan is generally site filled with concrete, Figure 35.14. For good wear resistance, a concrete strength of 5,000 psi is generally specified. Other tread finishes include a precast-concrete *drop-in tread* with a slip-resistant broom finish, Figure 35.15(a), and sheet steel with a raised, diamond-shaped checkered pattern, Figure 35.15(b). Factory-installed epoxy-aggregate fill or wear- and slip-resistant coatings can also be used.

STRINGERS

Stringers in a steel stair function as inclined beams, spanning from the floor to the landing and from the landing to the next floor. They generally consist of a structural-steel channel or steel plate ($\frac{3}{16}$ in. or $\frac{1}{4}$ in. thick is typical). The depth of stringers is a function of the stringer span and the structural loads required by codes. The tread-riser units span between the stringers. Figures 35.16 and 35.17 show typical details of support connections between the stringers and the floor of the building.

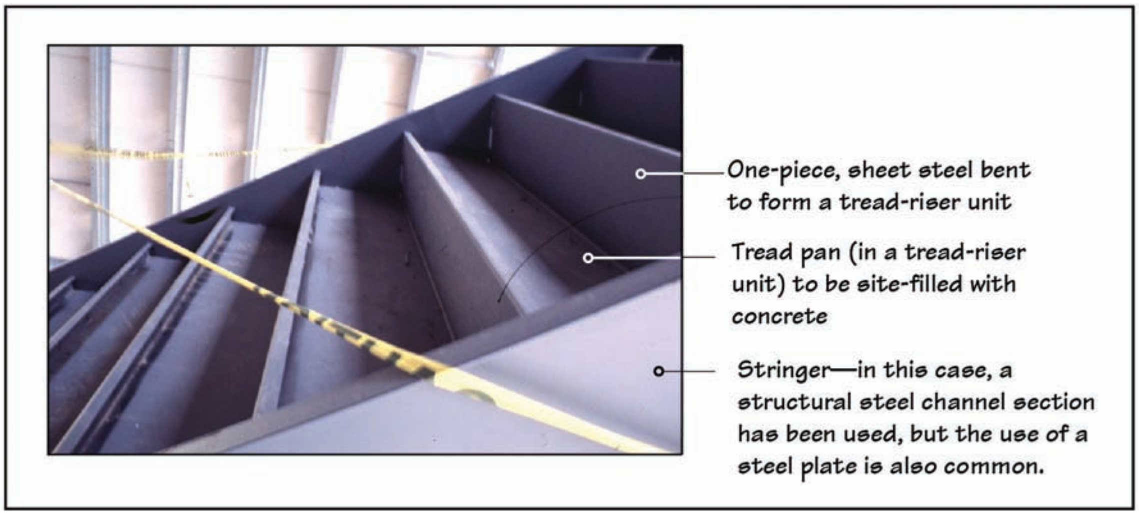

One-piece, sheet steel bent to form a tread-riser unit
Tread pan (in a tread-riser unit) to be site-filled with concrete
Stringer—in this case, a structural steel channel section has been used, but the use of a steel plate is also common.

FIGURE 35.13 A typical prefabricated steel stair consists of two stringer beams (stringers) to which tread-riser units made from sheet steel are welded; see Figure 35.14 for details. (In this stair, the guard unit and handrail have not yet been installed.)

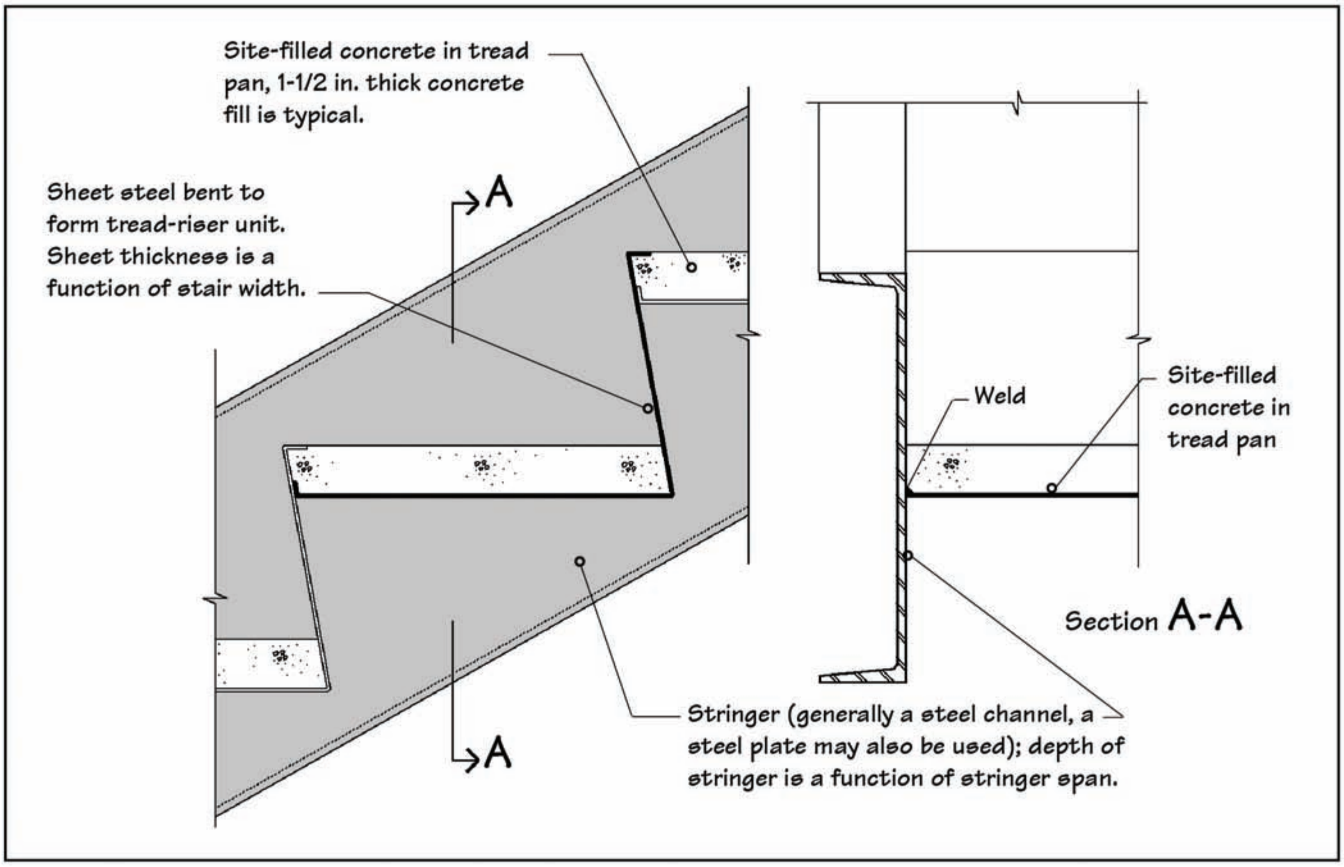

Site-filled concrete in tread pan, 1-1/2 in. thick concrete fill is typical.
Sheet steel bent to form tread-riser unit. Sheet thickness is a function of stair width.
A
A
Weld
Site-filled concrete in tread pan
Section A-A
Stringer (generally a steel channel, a steel plate may also be used); depth of stringer is a function of stringer span.

FIGURE 35.14 Typical detail of tread-riser units welded to stringers. In this detail, tread pans are site-filled with concrete; see Figure 35.15 for alternatives.

LANDING FRAME

The landing of a steel stair is generally framed with structural-steel members as a unit, called a *landing frame*. Typical details of connections between stringers and landings are shown in Figure 35.18. The finish on the landing is generally the same as that on the treads. Thus, where site-cast concrete is used on treads, the landing is also topped with concrete.

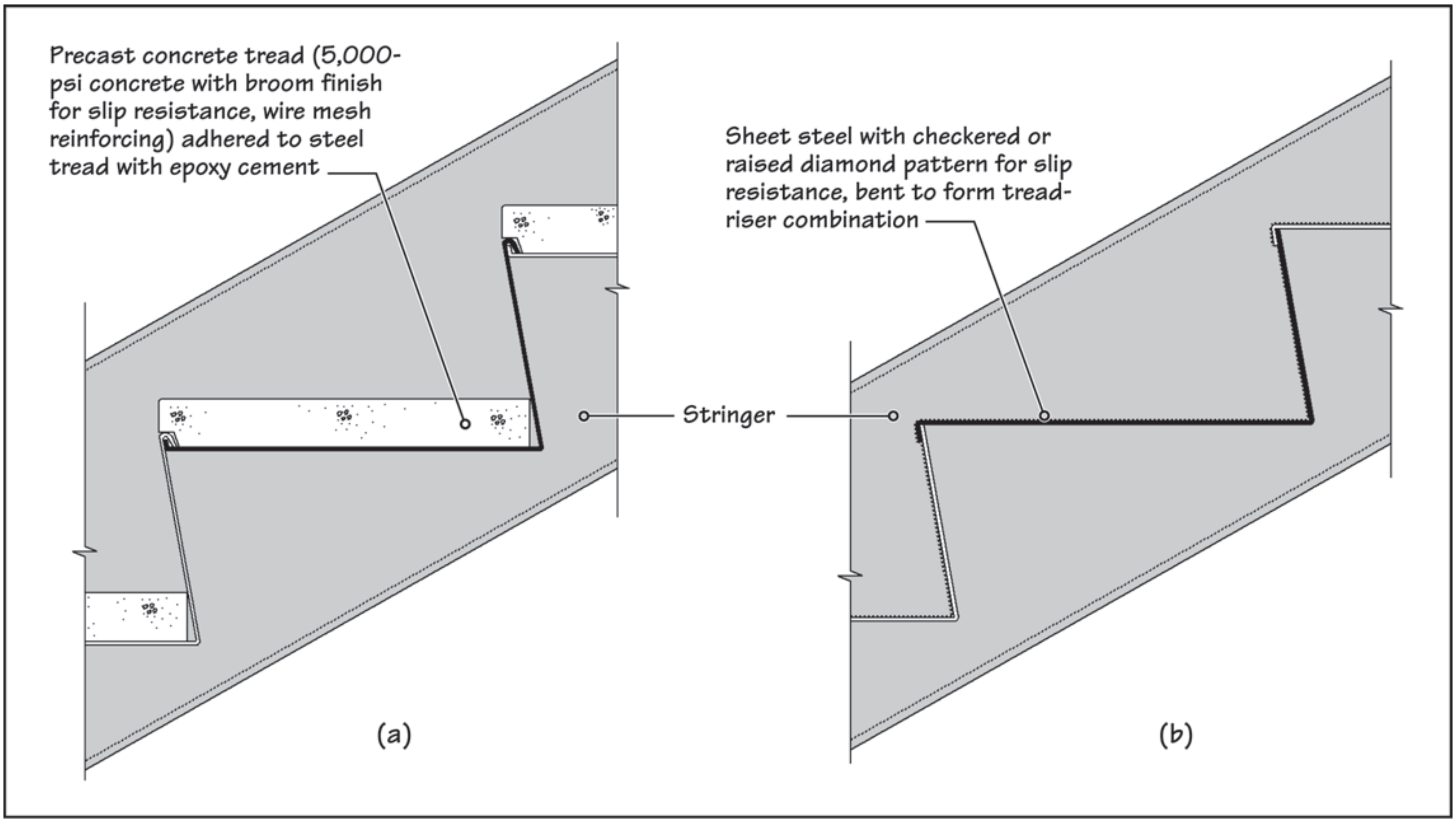

Precast concrete tread (5,000-psi concrete with broom finish for slip resistance, wire mesh reinforcing) adhered to steel tread with epoxy cement
Stringer
Sheet steel with checkered or raised diamond pattern for slip resistance, bent to form tread-riser combination
(a)
(b)

FIGURE 35.15 Two alternative details of tread-riser units in a steel stair (precast-concrete treads and checkered steel treads); another detail is shown in Figure 35.14.

The landing frame may be supported on a beam (specially introduced for the purpose) between the upper and lower floors of the building, on (masonry or concrete) stair-enclosure walls, or on columns independent of the structural frame of the building. In most buildings, however, the landing frame for a prefabricated steel stair is supported by suspending it from the upper-level floor beams with steel hanger bars, Figure 35.19.

A major advantage of a suspended landing is that it allows adjustment of the height of the landing with a few turns of the nuts. Additionally, the entire stair can be erected before constructing the walls of the stair enclosure.

35.4 CONCRETE STAIRS

Although concrete stairs can be precast and prefabricated, their use is limited because they are heavy, which increases the cost of transportation and installation. Most concrete stairs are site cast. As previously stated, the formwork for concrete stairs is intricate, which increases the cost and causes construction delays. Their use is, therefore, infrequent, even in buildings with a reinforced-concrete structural frame.

35.5 FREESTANDING CANTILEVERED STAIRS

In the various stair types discussed so far, each flight is supported at the floor and landing levels. The use of steel and reinforced concrete, however, allows the stairs to be constructed without any supports at the landings (designed as cantilevers and supported only at the floors). Cantilevered stairs, also referred to as *self-supporting stairs*, can be either U-shaped or circular in plan.

A cantilevered, self-supporting, U-shaped reinforced stair is shown in Figure 35.20(a). Figure 35.20(b) shows a cantilevered steel stair. In this stair, the stringers (of structural-steel channels) function as continuous spatially bent beams that are rigidly connected to the floor beams at both floors. Tread-riser units that span between stringer beams are made of structural-steel plate.

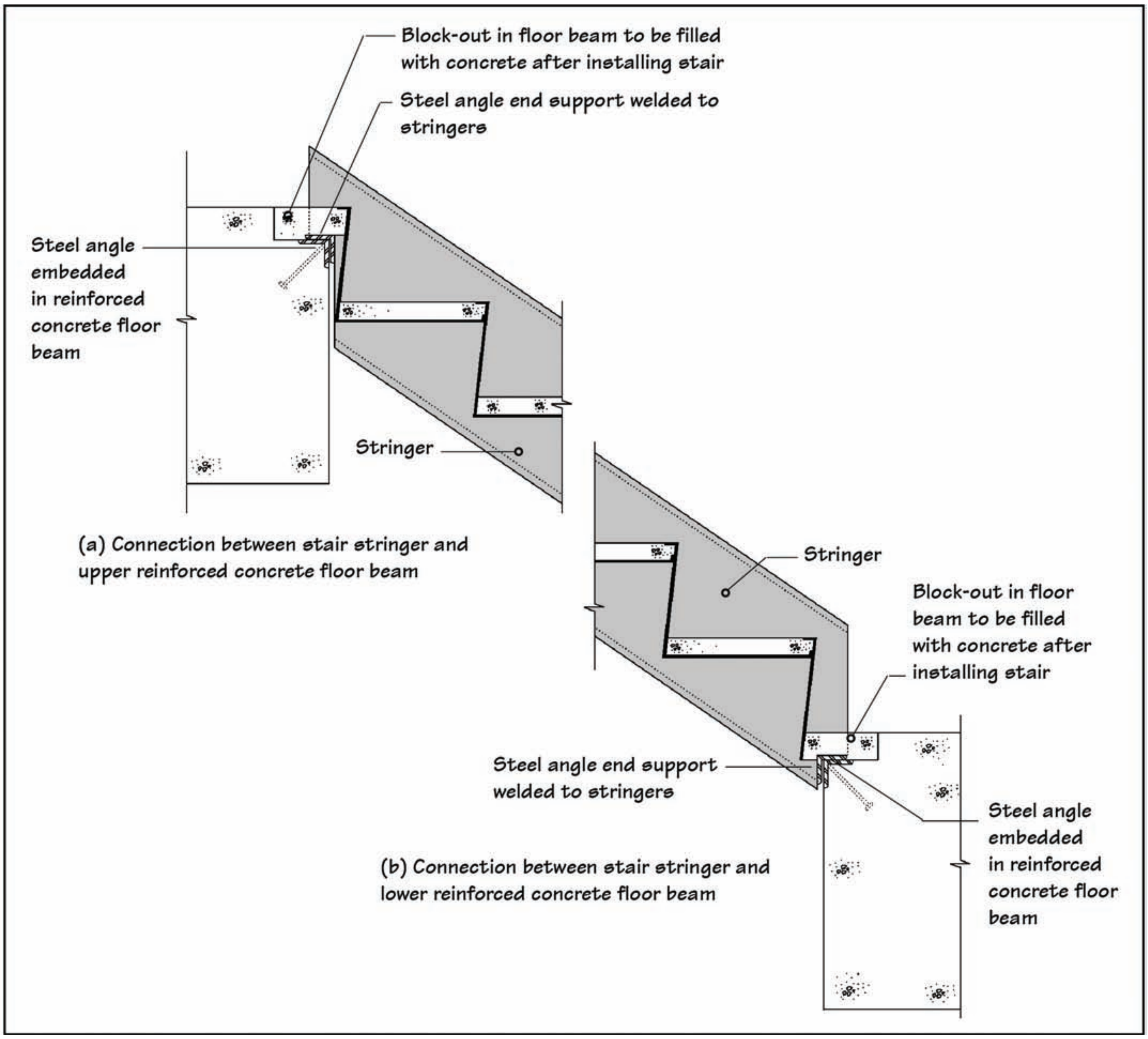

Block-out in floor beam to be filled with concrete after installing stair
Steel angle end support welded to stringers
Steel angle embedded in reinforced concrete floor beam
Stringer
(a) Connection between stair stringer and upper reinforced concrete floor beam
Stringer
Block-out in floor beam to be filled with concrete after installing stair
Steel angle end support welded to stringers
Steel angle embedded in reinforced concrete floor beam
(b) Connection between stair stringer and lower reinforced concrete floor beam

FIGURE 35.16 Typical details of connection between stringer and a reinforced concrete floor.

Self-supporting circular steel or concrete stairs can be constructed with or without landings. Called *helical* (or *helicoidal*) stairs, they are fairly common in steel, concrete, and wood. A helical stair is similar to a spiral stair but has no central column support.

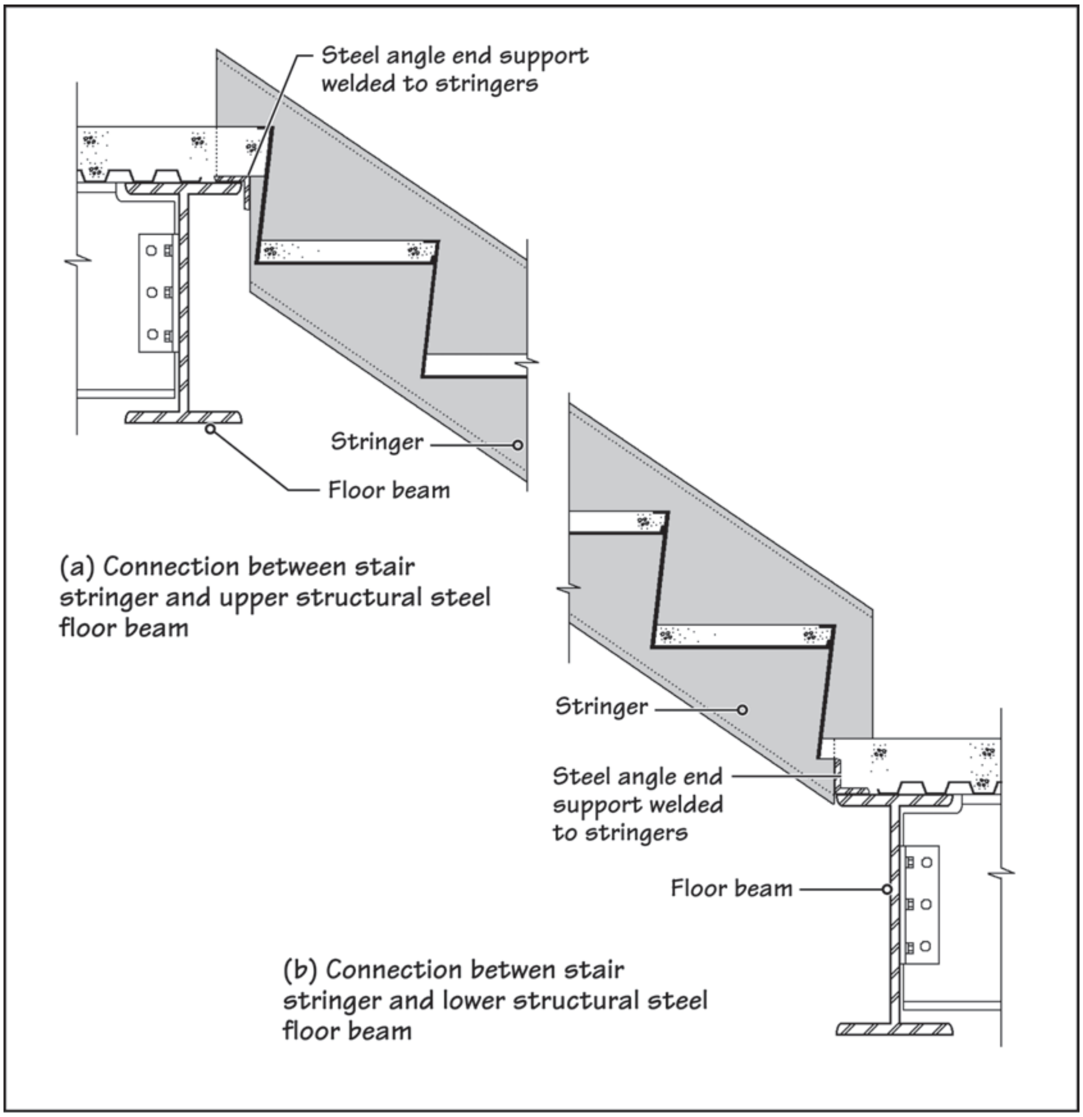

Steel angle end support
welded to stringers
Stringer
Floor beam
(a) Connection between stair
stringer and upper structural steel
floor beam
Stringer
Steel angle end
support welded
to stringers
Floor beam
(b) Connection betwen stair
stringer and lower structural steel
floor beam

FIGURE 35.17 Typical details of the connection between stringers and a steel-framed floor.

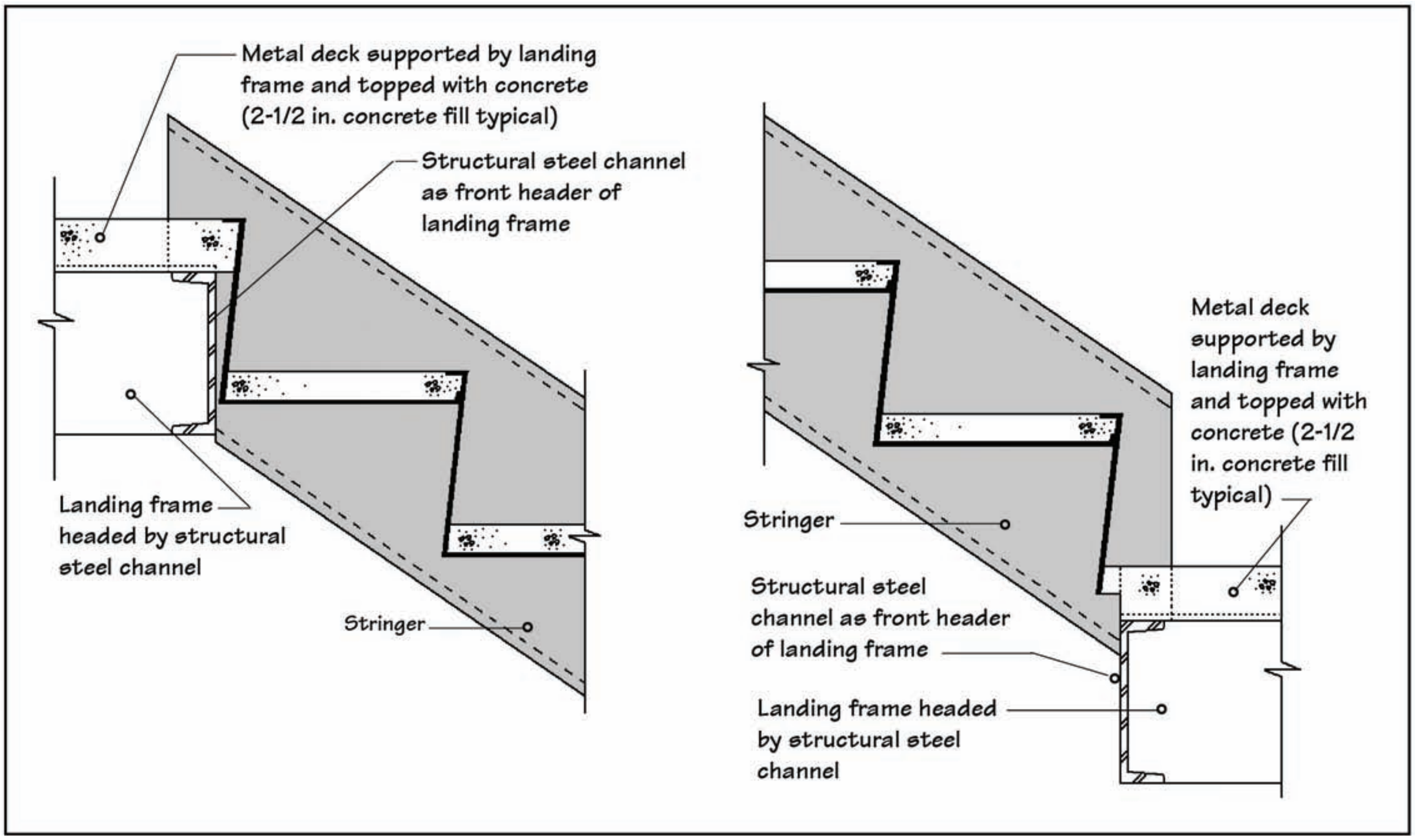

Metal deck supported by landing
frame and topped with concrete
(2-1/2 in. concrete fill typical)
Structural steel channel
as front header of
landing frame
Landing frame
headed by structural
steel channel
Stringer
Metal deck
supported by
landing frame
and topped with
concrete (2-1/2
in. concrete fill
typical)
Stringer
Structural steel
channel as front header
of landing frame
Landing frame headed
by structural steel
channel

FIGURE 35.18 Typical details of the connection between stringers and the landing frame.

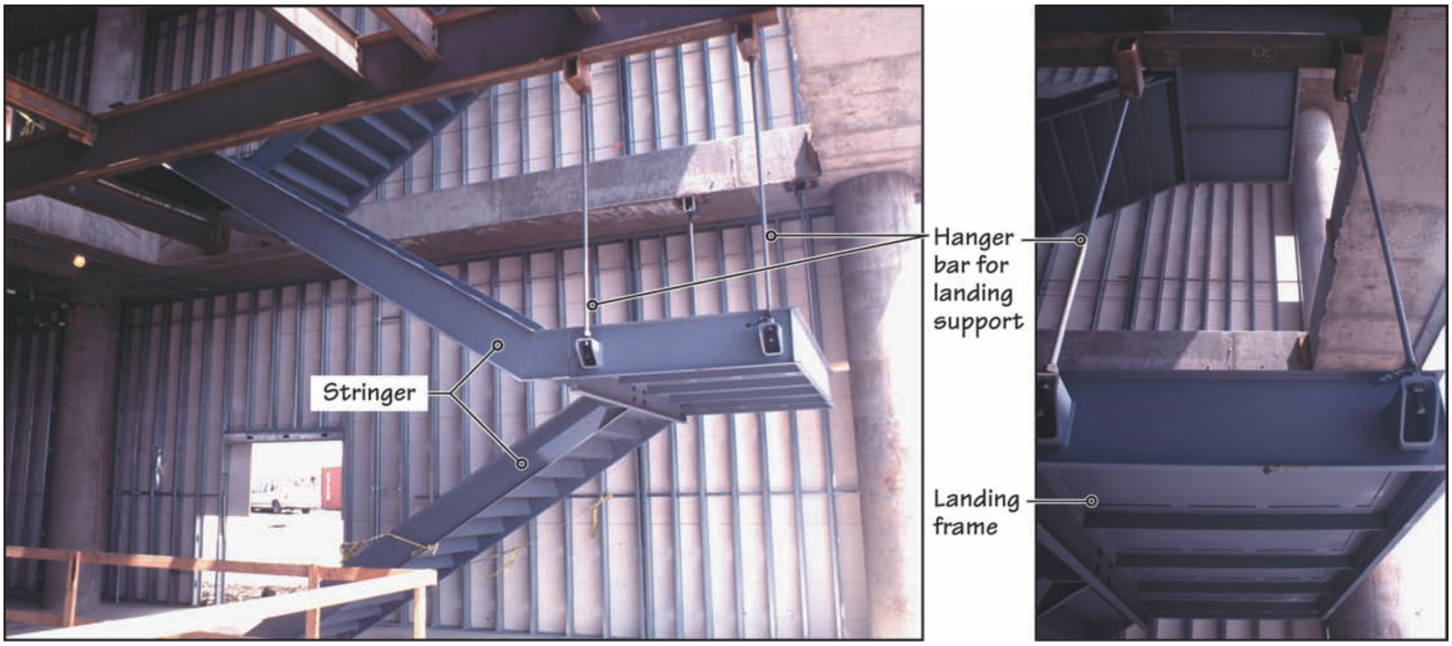

Hanger bar for landing support
Stringer
Hanger
bar for
landing
support
Landing
frame

FIGURE 35.19 A typical steel stair with a suspended landing—a commonly used landing support system for exit stairs in concrete and steel-frame buildings. (Guard units and handrail have not yet been installed.)

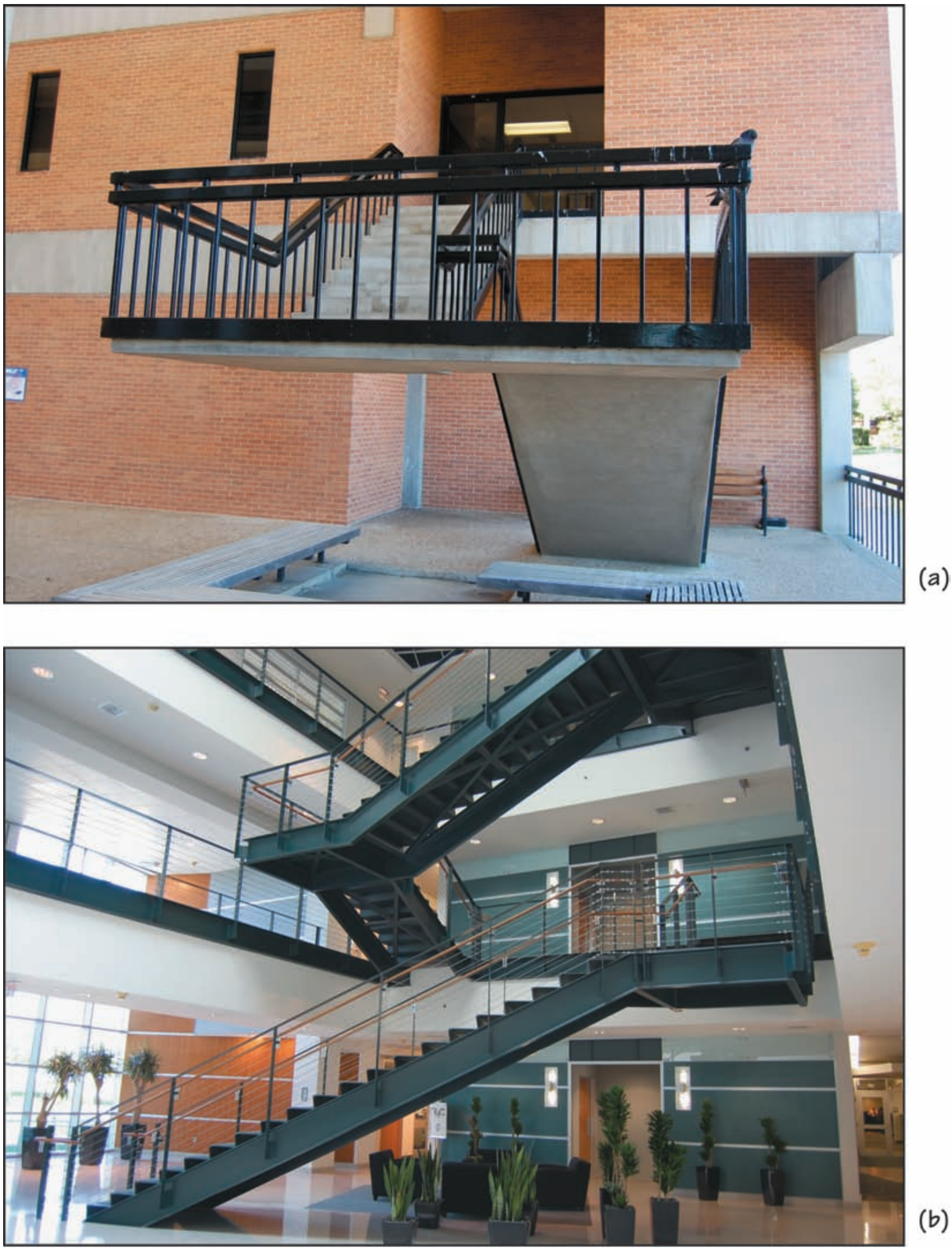


FIGURE 35.20 Two examples of cantilevered freestanding stairs, which are supported on the upper and lower floor structures, with no supports provided at mid-landing levels.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

14. In a typical wood stair, inclined beams that are cut to allow for the support of treads are called

a.	rough *stringers*.	**b.**	*finish stringers*.
c.	*balusters*.	**d.**	all of the above.
e.	none of the above.		

15. In a typical wood stair, the number of stringers required is determined by the
- **a.** width of the stair.
- **b.** spanning capacity of the carriage material.
- **c.** floor-to-floor height.
- **d.** thickness of the treads.
- **e.** all of the above.

16. In a prefabricated steel stair, treads and risers are generally two separate components.
a. True **b.** False

17. In a typical prefabricated steel stair, the number of stringers required is determined by the
- **a.** width of the stair.
- **b.** spanning capacity of the stringers.
- **c.** floor-to-floor height.
- **d.** spanning capacity of the tread-riser units.
- **e.** all of the above.

18. In a typical prefabricated steel stair, the stringers are cut to accommodate treads and risers.
a. True **b.** False

19. The stringers in a typical prefabricated steel stair are generally made of

a.	wide-flange sections.	**b.**	channel sections.
c.	plates.	**d.**	(a) and (b).
e.	(b) and (c).		

20. The landing frame in a typical prefabricated steel stair is generally hung from the building's structural frame.
a. True **b.** False

21. A self-supporting cantilevered stair is supported on intermediate landings only.
a. True **b.** False

22. A self-supporting cantilevered stair can be made only of reinforced concrete.
a. True **b.** False

REVIEW QUESTIONS

1. Provide the approximate expression used in proportioning the dimensions of the treads and risers of a stair. What is the basis for this expression? List building codes' restrictions on the dimensions of treads and risers.
2. With the help of at least two sketches, explain what a flight of stairs implies. What is the code-mandated maximum height of a flight of stairs?
3. Using a sketch, explain the difference between a handrail and guardrail of a stair, and give their code-mandated heights.
4. List the factors that determine the width of a stair.
5. Using sketches, explain how a steel stair's landing frame can be supported. Which one of these support methods is most commonly used?
6. Explain why a prefabricated steel stair is most commonly used even in buildings that are built with a reinforced-concrete frame structure.
7. Using a sketch, describe a cantilevered freestanding stair.

CHAPTER 36

Floor Coverings

CHAPTER OUTLINE

36.1 STRUCTURAL FLOOR AS SUBFLOOR FOR FLOOR COVERINGS

36.2 PERFORMANCE CRITERIA FOR THE SELECTION OF FLOOR COVERINGS

36.3 CERAMIC AND NATURAL STONE TILE FLOORING

36.4 NATURAL STONE PANEL FLOORING

36.5 TERRAZZO FLOORING

36.6 CARPET FLOORING

36.7 WOOD FLOORING

36.8 RESILIENT FLOORING

36.9 OTHER FLOOR-COVERING MATERIALS

Floors have had a broad range of finishes throughout the history of architecture, ranging from basic and utilitarian to complex and ornate. For contemporary buildings, an almost limitless number of floor-covering products are available. The design and articulation of floor surfaces are limited only by the designer's imagination. In fact, it is not unusual for the floor coverings to be the dominant element in building interiors where the budget permits. If the funds are not available, floor coverings are left basic.

Because of the huge variety in materials, colors, and patterns for floor coverings, only a few commonly used types are described here. Additionally, almost all contemporary floor coverings are proprietary. Therefore, the coverage focuses on the principles that underlie the construction and installation of all floor coverings.

36.1 STRUCTURAL FLOOR AS SUBFLOOR FOR FLOOR COVERINGS

The structural floor, often referred to as the *subfloor*, is constructed early in the building process. Therefore, it should be expected that the subfloor surface will become damaged due to the construction that takes place on or above it, necessitating some subfloor surface repairs before installing the floor covering.

TYPES OF SUBFLOORS

There are generally two types of structural floors, which are used as subfloors for floor coverings:

- *Concrete Subfloors:* Elevated concrete floors (cast-in-place concrete and concrete on metal deck) and concrete slabs-on-ground, Figure 36.1.
- *Wood Subfloors:* Wood panels supported by wood light-frame (or cold-formed steel-frame) members, Figure 36.2.

SUBFLOOR CHARACTERISTICS

The long-term durability of floor coverings depends on the quality and condition of the subfloor. Some of the important requirements of a subfloor are as follows:

- *Structural Adequacy:* The subfloor should have the required strength and stiffness to support the weight of the floor covering and the attendant underlayment, mortar, and so on, without undue deflection.
- *Dry:* Subfloors must be sufficiently dry because adhesives will not adhere properly to a wet or partially wet surface. Additionally, excessive moisture in a concrete subfloor will damage floor coverings as the moisture moves upward through concrete; see margin note.

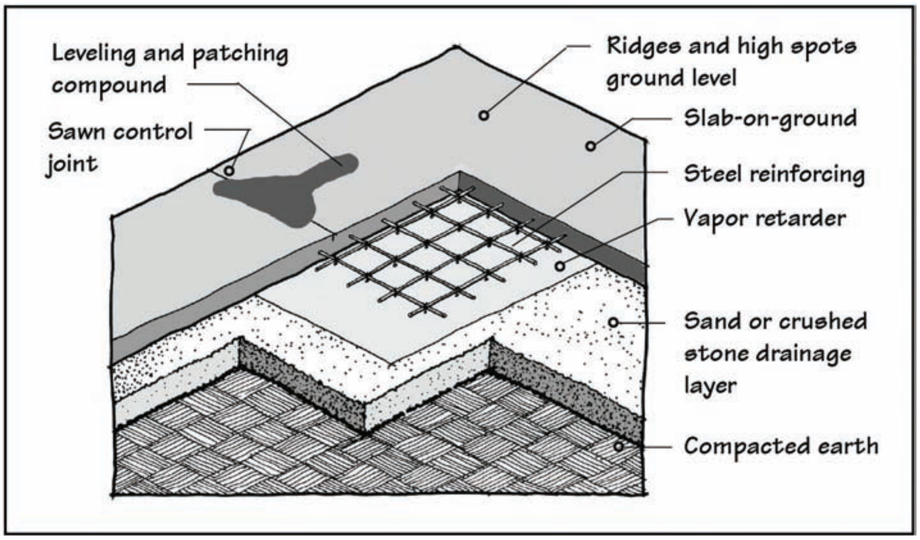

Leveling and patching compound
Sawn control joint
Ridges and high spots ground level
Slab-on-ground
Steel reinforcing
Vapor retarder
Sand or crushed stone drainage layer
Compacted earth

FIGURE 36.1 Typical detail of concrete slab-on-ground including the leveling and patching of the slab before laying the floor covering (see also Figure 36.26). Grinding and patching may also be required on an elevated concrete slab.

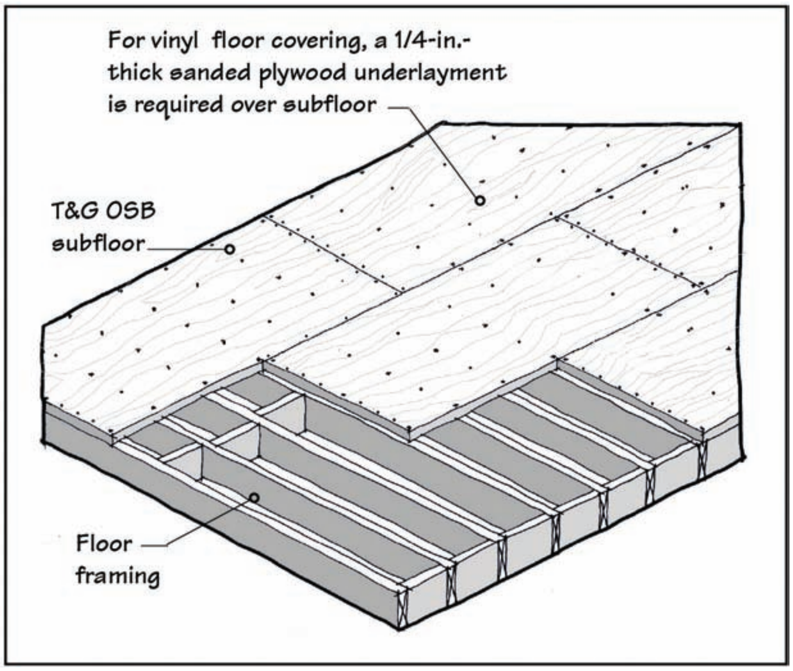

For vinyl floor covering, a 1/4-in.-thick sanded plywood underlayment is required over subfloor
T&G OSB subfloor
Floor framing

FIGURE 36.2 Typical preparation for floor coverings on a wood subfloor.

- *Flat, Smooth, and Level:* Subfloors should be flat, smooth, level, and free from irregularities such as rough spots, cracks, depressions, ridges, and holes. Many floor coverings are thin and flexible, and imperfections in the subfloor will telegraph through the product and become permanent imperfections in the floor covering. Generally, subfloors should be level, with no more than $\frac{1}{8}$ in. to $\frac{3}{16}$ in. of vertical change in any 10 ft horizontal dimension. Deflection of the subfloor also contributes to surface irregularities.
- *Clean and Free of Foreign Materials:* There should be no foreign materials, including dust, solvents, paint, wax, and oil, on the surface of the subfloor.

36.2 PERFORMANCE CRITERIA FOR THE SELECTION OF FLOOR COVERINGS

There are several performance factors that should be considered when selecting floor coverings, their performance rating evaluated per the applicable standards. Important factors to be considered are as follows:

- *Slip Resistance:* Many injuries result annually from falls on slippery surfaces, particularly when wet. In areas where this is a hazard, surface conditions must provide adequate resistance to slipping. This is measured by laboratory testing that establishes a numerical value known as the *coefficient of friction*.
- *Durability:* Floor coverings may be subjected to many types of use and exposure to environmental impacts. These include wear and damage due to the abrasive impact of pedestrian and other types of traffic; staining and damage from liquids, chemicals, and reagents; degradation from exposure to ultraviolet radiation from skylights or large windows; and issues related to water and moisture.
- *Flammability:* Building codes require that floor coverings resist flame propagation, see Section 7.8.
- *Acoustical Properties:* Floor coverings impact the transmission of sound in several ways. Carpets and resilient floor coverings can reduce impact sound, lowering the noise level within space and its transmission to spaces below, see Section 8.5.
- *Hygienic Qualities:* In some applications, such as a hospital or commercial kitchens, a floor covering should not harbor dirt and bacteria. In such cases, floor coverings that are easily cleaned, jointless, and made of inorganic materials are preferred to prevent mold and mildew growth.
- *Walking Comfort:* When people will be constantly standing on, or walking over a floor covering, underfoot comfort is important. Hard, unyielding surfaces can cause walker fatigue.
- *Sustainability:* Maintaining good indoor air quality is one of the criteria that contribute to a sustainable environment. Floor coverings and adhesives that do not outgas volatile organic compounds are important parts of the sustainability criteria included in the LEED rating system, see Sections 10.7 and 10.8.
- *Maintenance Requirements:* Maintenance is an ongoing expense for every building. For every floor covering, there is a prescribed maintenance procedure to ensure the longest possible performance time. Some floor coverings are more time consuming and expensive to maintain than others, a factor that must be considered in terms of long-term maintenance goals and budgets for the building.

36.3 CERAMIC AND NATURAL STONE TILE FLOORING

Because of their hard-wearing surfaces, resistance to water penetration and mold growth, ceramic and natural stone tiles are commonly used as floor-covering material in lobbies and foyers of commercial buildings. Natural stone is more versatile than ceramic tiles because of its greater durability and aesthetic qualities, but is more expensive. Therefore, most residential kitchens and bathroom floors in North America are finished with ceramic tiles. Both ceramic and natural stone tiles come in a variety of face dimensions and thickness with corresponding trims (transition pieces between the floor and the vertical surfaces, such as walls and columns). The Tile Council of North America (TCNA) publishes the *TCNA Handbook for Ceramic, Glass, and Stone Tile Installation*, which contains expert guidance on materials and installation practices.

NOTE

Moisture Content of a Concrete Slab-on-Ground

The moisture content of a concrete slab-on-ground should be low for all types of floor coverings. A two-part strategy is used to ensure this requirement: (a) provide a vapor retarder below the slab, as shown in Figure 36.1 and (b) verify that the concrete in the slab is sufficiently dry before laying the floor covering. These requirements are particularly important if the floor coverings are polymer based (e.g., vinyl tiles, thin-set terrazzo, and carpets; carpet fibers and backings are polymeric materials). Polymer-based floor coverings are not vapor permeable, that is, they do not allow water vapor to pass through them. Therefore, as the water in the slab converts to water vapor, it delaminates the floor covering from the slab. (Remember from Chapter 6 that water vapor pressure is generallya very high.) In other words, a polymer-based floor covering requires a vapor retarder of extremely low permeability under a slab-on-ground.

If the floor covering is Portland cement based, such as Portland cement terrazzo, which is vapor permeable, the delamination of floor covering is of little concern. However, the use of a vapor retarder under such floors is still important, particularly if the space is a conditioned space.

To check the dryness of the slab, the test procedures, such as those stipulated in ASTM F2170 and ASTM F1869, should be used. However, a rough and ready procedure is to place a 3 ft × 3 ft sheet of glass on the slab, and fully adhere its edges with a strong vapor impermeable tape. If after 72 hours, condensation marks appear between the glass and the concrete slab and/or the tape comes off easily, the slab is not dry and not ready for floor covering.

CERAMIC TILE CHARACTERISTICS AND TYPES

Ceramic tiles are made from natural clay, porcelain, or other ceramic materials. The exposed face is either glazed or left unglazed and then fired to a temperature sufficient to produce the necessary physical properties. Glazed tiles have a glossy or matte exposed surface, while the unexposed (back) surface of tiles is always rough and uneven to provide good adhesion to the subfloor through the intervening mortar. The glaze protects the tile body against water absorption and provides for a wide range of colors.

Glazes can be opaque, transparent clear, or colored clear, and sheens may be matte (low or no gloss), semi-matte (moderate gloss), or bright (high gloss). Architects and interior designers often combine matte and semi-matte tiles (and of various sizes) in the same floor to produce a measure of interest in floor covering. The most commonly used size of ceramic tiles are 12-in., 15-in., 18-in., and 24-in. square with a thickness ranging from $\frac{1}{4}$ in. to $\frac{3}{8}$ in.

NATURAL STONE TILE CHARACTERISTICS AND TYPES

While ceramic tile is a manufactured material, stone tile is produced from natural stone quarries. Most commonly used natural stone for flooring is granite, marble, and slate. Because ceramic tiles go through drying shrinkage when fired, tile size is not absolutely uniform. Therefore, ceramic tile flooring requires wider joints between tiles which are filled with grout. Natural stone tiles can be cut to uniform sizes and thickness (commonly called *gauged tiles*), which allows them to be butt-jointed with an extremely tight grout lines.

The most commonly used size of stone tiles is the same as for the ceramic tiles, that is, 12-in., 15-in., 18-in., and 24-in. square with a thickness of $\frac{3}{8}$ in. (1 cm). The majority of stone tiles have polished finish. Where a matte fish is desired, a honed finish is used (see Section 25.7 for finishes on natural stone).

STIFFNESS OF SUBFLOOR

Because both ceramic and natural stone are brittle materials and the thickness of floor tiles is small (seldom exceeding $\frac{3}{8}$ in.), it is important that the subfloor be reasonably stiff so that its deflection under live loads is small. Excessive deflection of the subfloor will lead to the cracking of tiles and/or the grout lines. Properly designed (reinforced concrete or post-tensioned) concrete slab-on-ground and an elevated concrete slab are quite stiff and are the best subfloor options for tile flooring. A typical detail of tile flooring over an elevated concrete-slab-on-ground is shown in Figure 36.3(a).

For a wood subfloor, the use of at least 1-in.-thick tongue-and-groove (T&G) OSB or plywood panels supported on closely spaced floor joists is recommended to provide a reasonably stiff subfloor. Manufacturers of ceramic and natural stone tiles do not recommend their materials to be used on a wood subfloor with joist spacing greater than 16 in. The use of a cement (or fiber-cement) backer board between the wood subfloor and the tiles is a

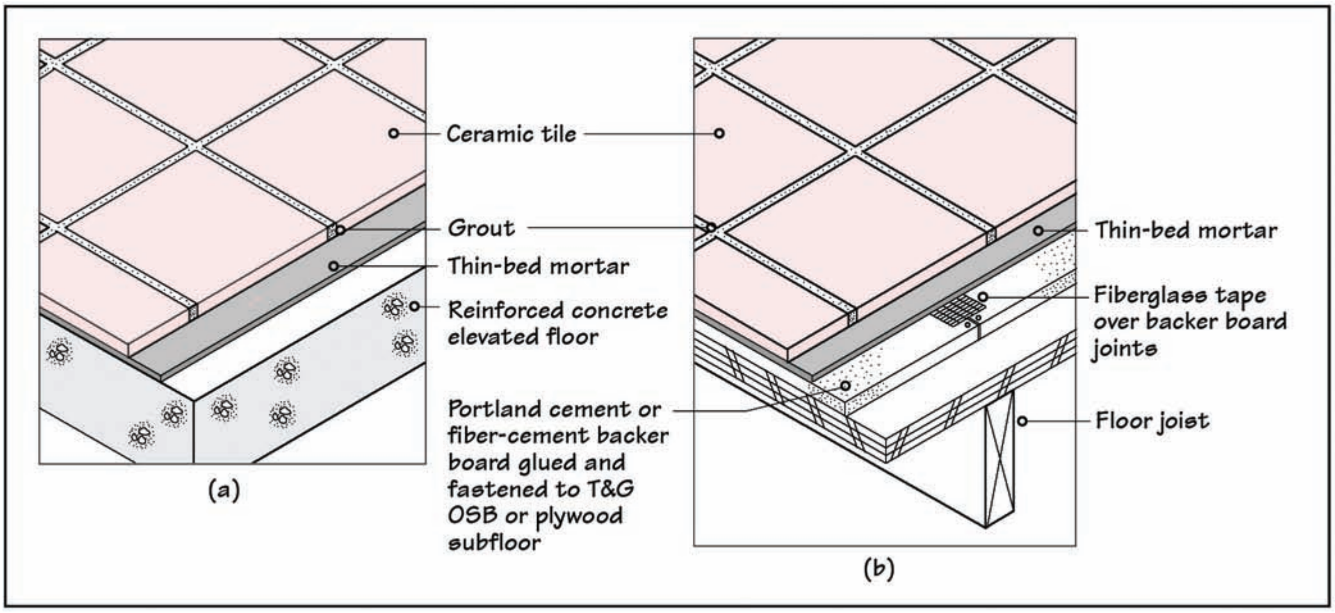

Ceramic tile
Grout
Thin-bed mortar
Reinforced concrete elevated floor
Portland cement or fiber-cement backer board glued and fastened to T&G OSB or plywood subfloor
(a)
Thin-bed mortar
Fiberglass tape over backer board joints
Floor joist
(b)

FIGURE 36.3 **(a)** Ceramic tile floor covering over an elevated reinforced-concrete structural floor; the details of ceramic tile floor covering over a concrete slab-on-ground are similar except the addition of a vapor retarder and sand cushion under the slab, as shown in Figure 36.1. **(b)** Ceramic tile floor covering over a wood subfloor.

recommended addition because it increases the stiffness of the floor and provides other desirable properties, such as water resistance and better adhesion of the tiles, Figure 36.3(b).

THICK-BED MORTAR VERSUS THIN-BED MORTAR

The installation of floor tiles on the subfloor begins by laying of the mortar bed. Apart from functioning as an adhesive, the mortar bed compensates for the unevenness in the surface of the subfloor and that of the tiles by providing a cushion between them. The traditional mortar bed consisted of a mixture of Portland cement, sand, and water, Figure 36.4. Known as *thick-bed mortar*, its thickness varies from 1 in. to 2-$\frac{1}{2}$ in. depending on the unevenness of the subfloor, nonuniformity in tile thickness, and face dimensions of tiles. A more uneven subfloor, greater variation in tile thickness, larger face dimensions of tiles, or large natural stone panels require greater thickness of mortar bed. A thick-bed mortar is also required if the floor slopes to drains, such as in a public shower room or an individual shower enclosure.

Once the mortar bed is level and still green (i.e., before it begins to cure), the tiles are laid on the mortar bed. If the tiles are set after the bed has (somewhat) cured, its surface is coated with Portland cement and water slurry, referred to as the *bond coat*. The bond coat may also be used even when the mortar bed is green for better adhesion of tiles, as shown in Figure 36.4.

Thick-bed mortar has largely been replaced by preblended mortars that do not require on-site mixing of materials, such as that needed for a thick-bed mortar. The composition of thin-bed, preblended mortars is proprietary to the manufacturer, but they generally contain Portland cement modified with polymers, such as latex or acrylics. The polymer addition increases mortar's workability, improves adhesion to subfloor and mortar's flexibility, requires less labor, and is more economical. Referred to as *thin-bed mortars*, the preblended mortars need only be $\frac{1}{4}$ in. to $\frac{3}{8}$ in. thick depending on the face dimensions of tiles. The greater the face dimensions, the thicker is the mortar.

Thin-bed mortars cannot be used with large-size tiles or highly uneven subfloor surface. Manufacturers of thin-bed mortars limit the size of tiles (generally to a maximum of 24 in. × 24 in.) and specify the maximum variation in subfloor surface elevation for their mortars depending on tile size and its thickness. Thick-bed mortars are therefore required where the tiles are large, such as under large natural stone panels, described in the next section.

FLOOR TILE INSTALLATION USING THIN-BED MORTAR

A notched trowel is the primary tool used to lay the mortar. The flat side of the notched trowel helps spread the mortar and its notched side produces grooves by combing into the mortar. The grooves in the mortar allow any air under the tile to escape when the tile is pressed over the mortar, with the purpose of eliminating air pockets and providing as close to full coverage of the tile with mortar as possible, Figure 36.5.

With large floor tiles, the installer will spread additional mortar over some notched areas, wiggle the tile over the mortar while pressing it down to eliminate any leftover air pockets,

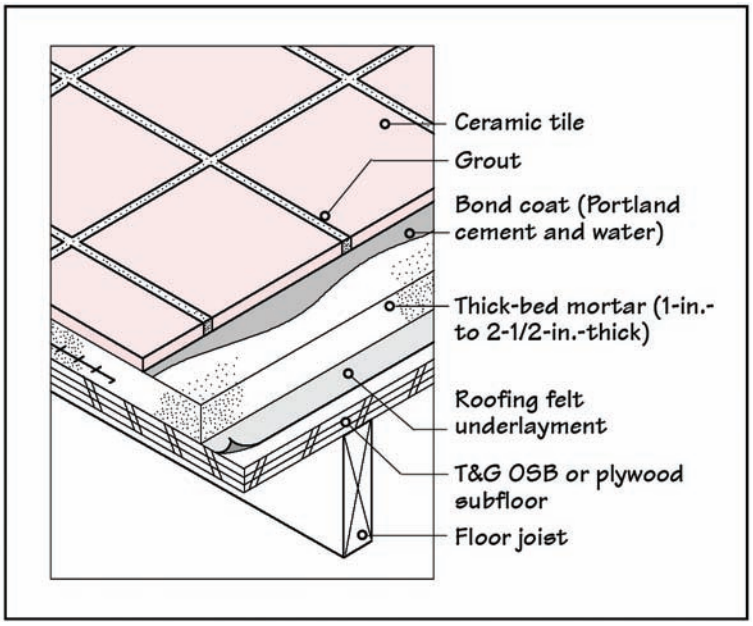

Ceramic tile
Grout
Bond coat (Portland cement and water)
Thick-bed mortar (1-in.- to 2-1/2-in.-thick)
Roofing felt underlayment
T&G OSB or plywood subfloor
Floor joist

FIGURE 36.4 Ceramic tile floor covering set over a thick-bed mortar on a wood subfloor. The bed may be reinforced with a wire mesh or metal lath if the subfloor deflection is high. For a reinforced-concrete subfloor, the detail is similar, but felt underlayment and wire mesh are not needed.

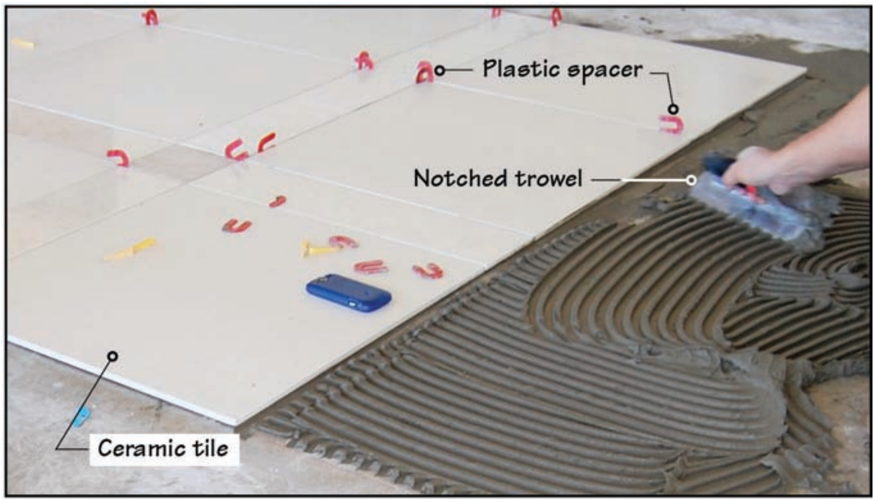


FIGURE 36.5 An installer laying thin-bed mortar under ceramic tiles using a notched trowel.

Figure 36.6. Plastic spacers between tiles, shown in Figures 36.5 and 36.6, help to ensure uniform width of joints between tiles.

Joint width is a function of the variation in the face dimensions of tiles. The minimum joint width recommended is three times the actual variation in face dimensions. For example, if the actual variation in tile dimensions is $\frac{1}{16}$ in., the minimum recommended joint size is $\frac{3}{16}$ in. As part of quality control, the installer will randomly remove a tile just laid and examine its back surface to ensure that mortar is covering its entire back surface, Figure 36.7(a). Additionally, the installer will frequently check the flatness of the floor with a carpenter's level, Figure 36.7(b).

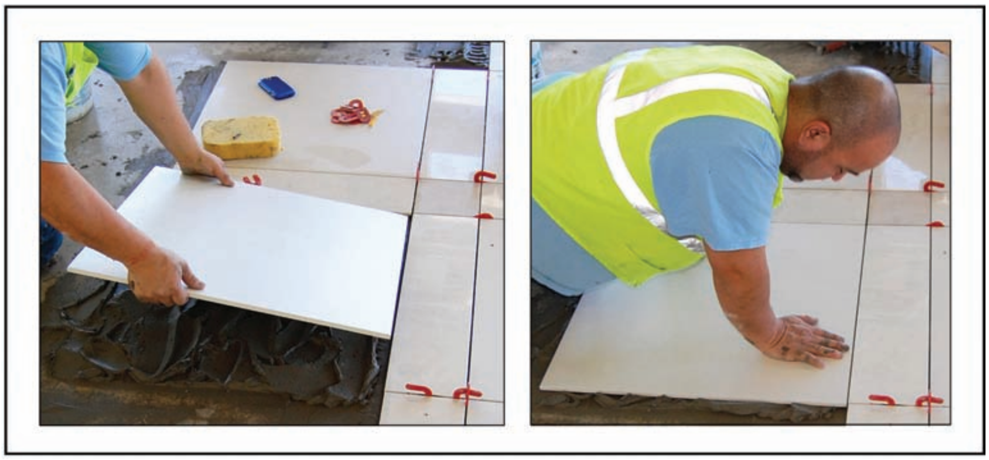


FIGURE 36.6 An installer sets a ceramic tile on a thin-bed mortar, followed by gently pressing the tile and squiggling it around to eliminate air packets under it.

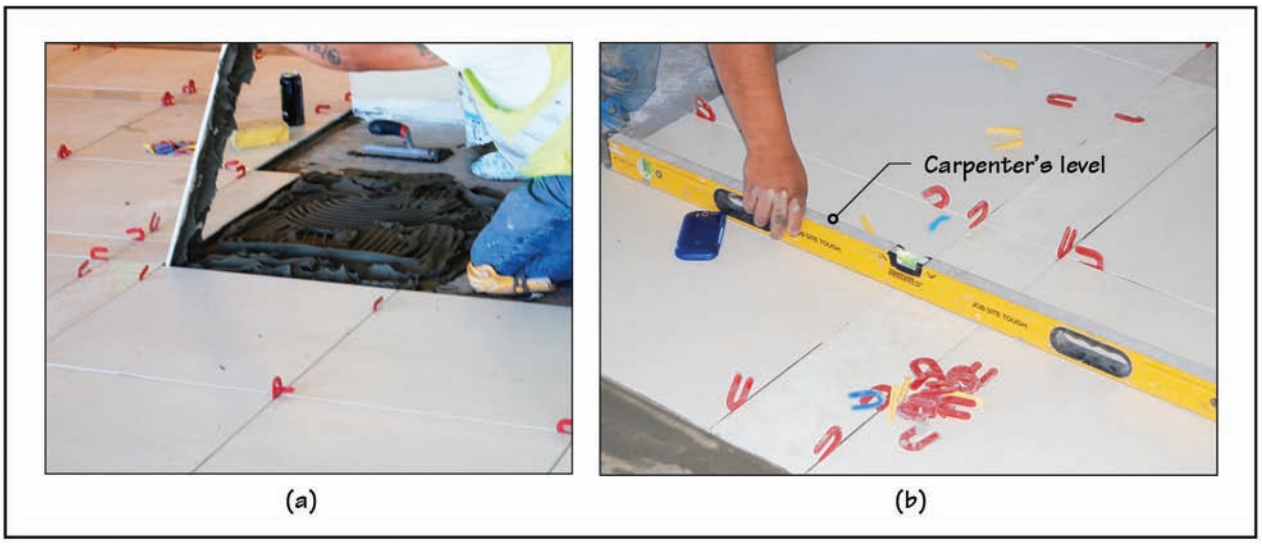


FIGURE 36.7 **(a)** As part of quality control measure, an installer will randomly remove a tile just laid and inspect its back surface for mortar coverage determination. A partial coverage implies the presence of air pockets. **(b)** During the process of setting the tiles, the installer will frequently check the flatness of the floor using a carpenter's level.

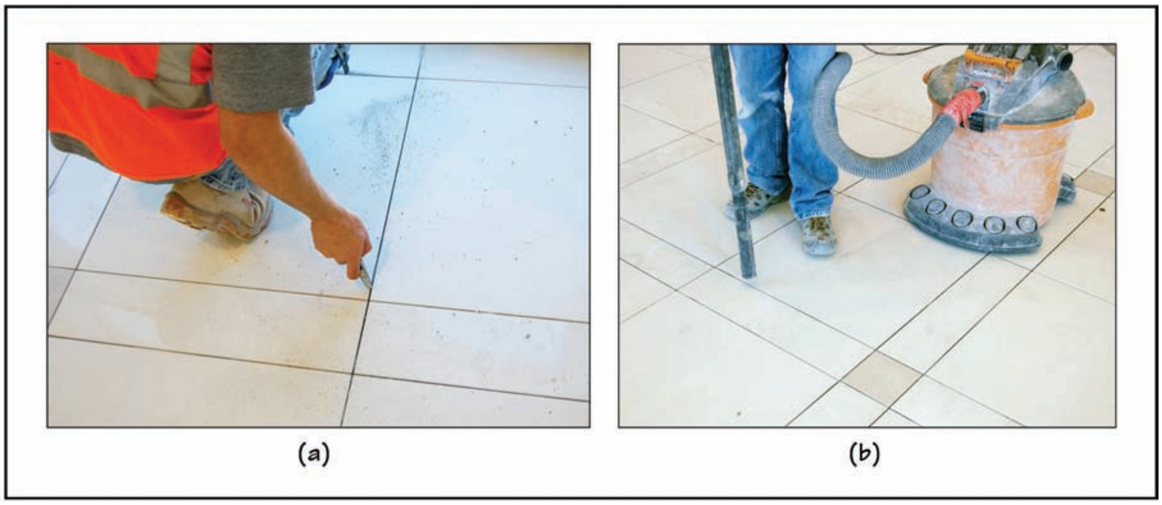


FIGURE 36.8 **(a)** In preparation for grouting the joints, the spacers are removed and the joints between tiles are cleared of debris and unintended mortar deposits to make space for the grout. **(b)** The floor is also vacuum cleaned before grouting.

The next two operations after laying the tiles are grouting the joints between tiles and installing the trim pieces. Grout fills the joints between tiles and is undertaken after the mortar has partially cured, generally 24 hours after the tiles have been set. Prior to grouting, the joints between tiles are cleared of dust and debris to expose sufficient clear joint space for grout coverage, and the floor is vacuum cleaned, Figure 36.8. Subsequently, the grout is smeared into the joints with a rubber float, Figure 36.9. Manufacturers that provide the mortar also provide the grout in various shades and colors.

Because the grout sets fairly quickly, it is important to clean the grout smears on the face of the tiles using a sponge and water bucket in which the sponge is frequently rinsed and wrung, Figure 36.10. Usually one installer will grout the tiles and another worker will follow within 20 minutes or so to clean the smears. Otherwise, it becomes difficult to remove the smears.

The installation of base trim follows the setting and grouting of floor tiles. The base trim pieces with a ceramic tile floor may either be of ceramic or natural stone. The process of their installation is similar to the installation of tiles, Figure 36.11. A finished ceramic tile floor looks somewhat as shown in Figure 36.12.

36.4 NATURAL STONE PANEL FLOORING

Natural stone panels are the same material as natural stone tiles except that the panels used for floor covering have larger face dimensions and thickness than the tiles, and can be up to 8 ft in one of the two directions. They are typically available in thickness of $\frac{3}{4}$ in. (2 cm) or $1\frac{1}{4}$ in. (3 cm). The finishes commonly used for stone panels are also essentially the same

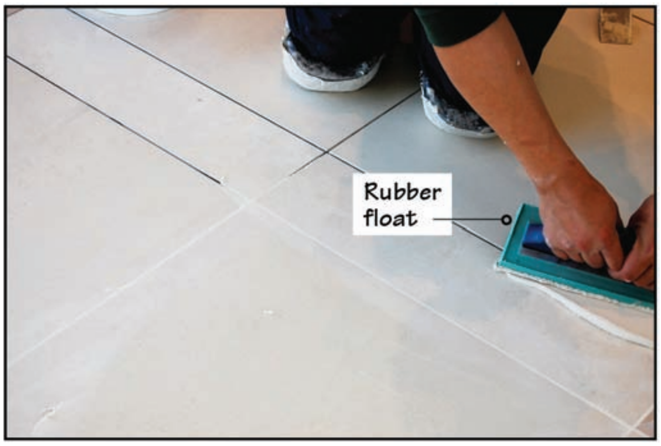


FIGURE 36.9 The grout is pressed into the joints between tiles using a rubber float.

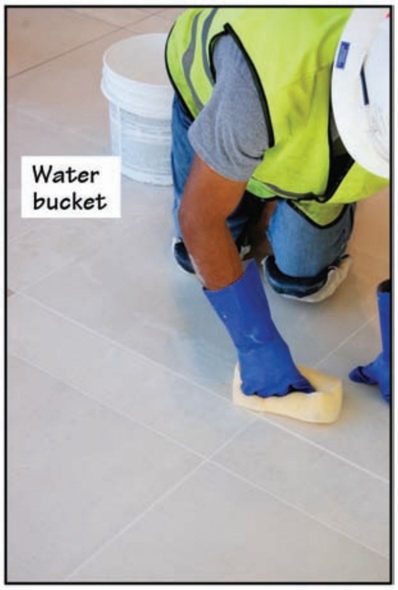


FIGURE 36.10 Within about 20 minutes of grouting the joints, the grout smears are cleaned using a sponge pad frequently rinsing and wringing it in a bucket of water with cleaning additives recommended by the grout manufacturer.

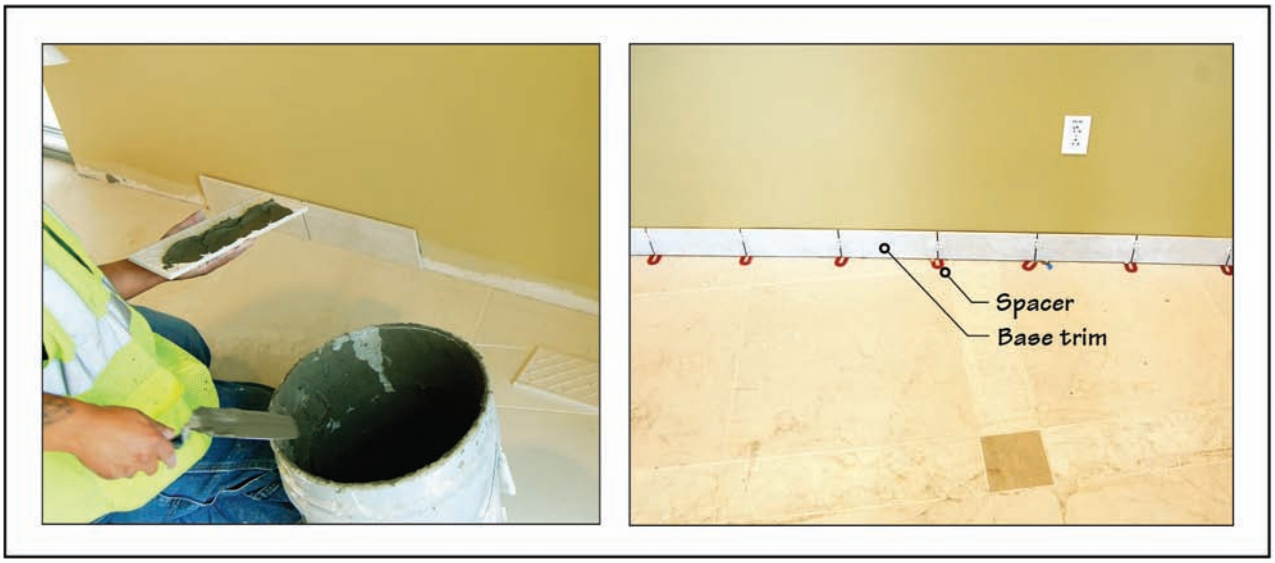


FIGURE 36.11 After the tiles have been set and grouted, base trims are set with mortar and their joints grouted, a process that is similar to that used for the floor tiles. In this floor, the base trim is of $\frac{1}{2}$-in.-thick marble tiles.

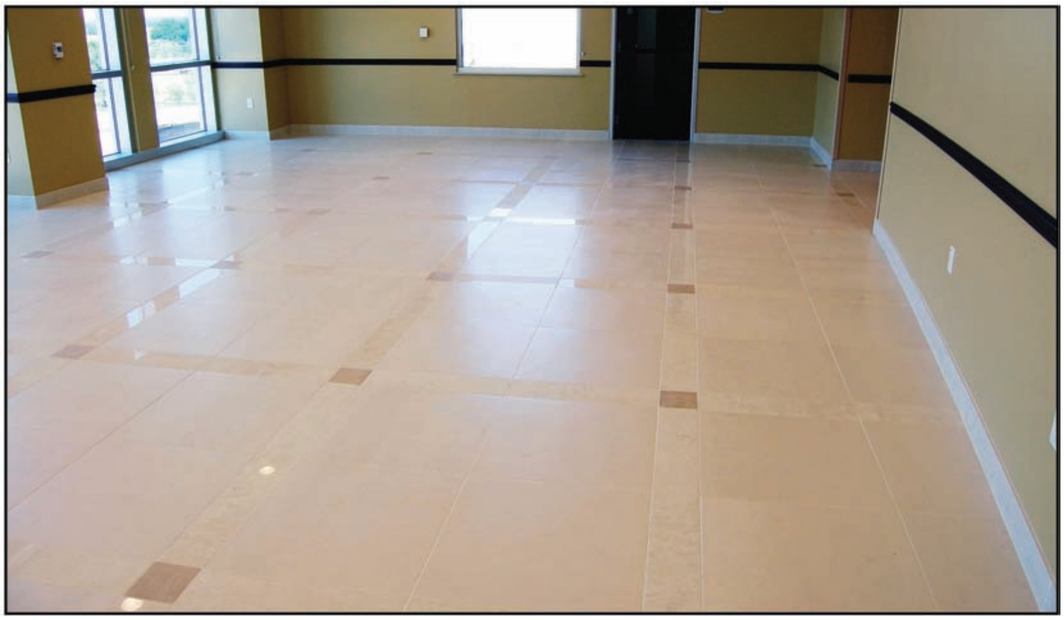


FIGURE 36.12 A completed ceramic tile floor, combining tiles of different sizes, shades, and gloss (matt, semi-gloss, and high-gloss finish).

as on stone tiles—polished or honed. Stone panel flooring is used in lobbies and foyers of high-end offices and other important buildings.

INSTALLATION OF STONE PANELS

Because of their large face dimensions and the consequent high probability of the mismatch between the top of the subfloor surface and the bottom of the panels, producing numerous points of stress concentrations, the stone panels must be set on a thick-bed mortar, Figure 36.13. While the mortar bed is still plastic, it is covered with a bond coat of Portland cement slurry and the panel is set over it. As with the installation of the tiles, the mortar bed is prepared panel by panel, and as one panel has been set, the mortar bed for the subsequent panel is prepared, Figure 36.14. Plastic spacers are used to maintain uniform joint width between panels and the floor elevation is frequently checked.

After the mortar has cured sufficiently, the joints are grouted. It should be noted that because of the uniformity of panel sizes, the grout joints in stone panel flooring may be as small as $\frac{1}{16}$ in. Base trim pieces are installed in the same way as for tile flooring, shown in Figure 36.11. A finished natural stone panel floor looks somewhat as shown in Figure 36.15.

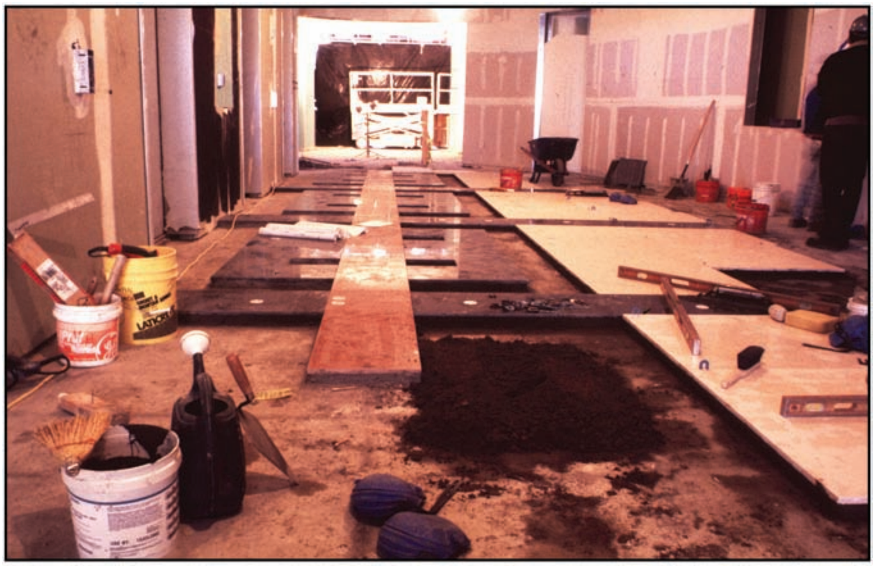


FIGURE 36.13 Natural stone panel flooring in progress in the lobby of an office building. The finished floor is shown in Figure 36.15.

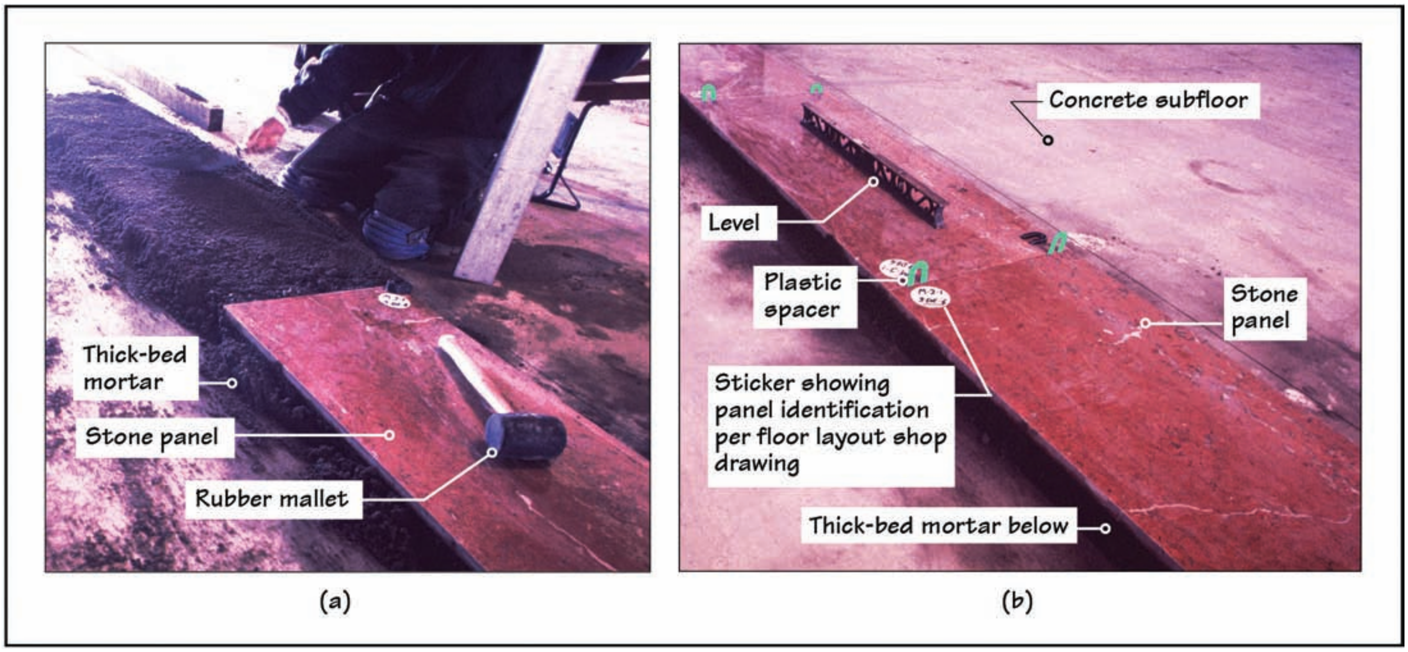

Thick-bed mortar
Stone panel
Rubber mallet
(a)
Concrete subfloor
Level
Plastic spacer
Stone panel
Sticker showing panel identification per floor layout shop drawing
Thick-bed mortar below
(b)

FIGURE 36.14 **(a)** The thick-bed mortar is being readied for the installation of the next stone panel. The rubber mallet is used to adjust the elevation of the panel. **(b)** Plastic spacers are used to keep the joints between panels uniform in width. The circular stickers in the corner of panels are panel numbers that are coordinated with the shop drawings that show the layout of panels.

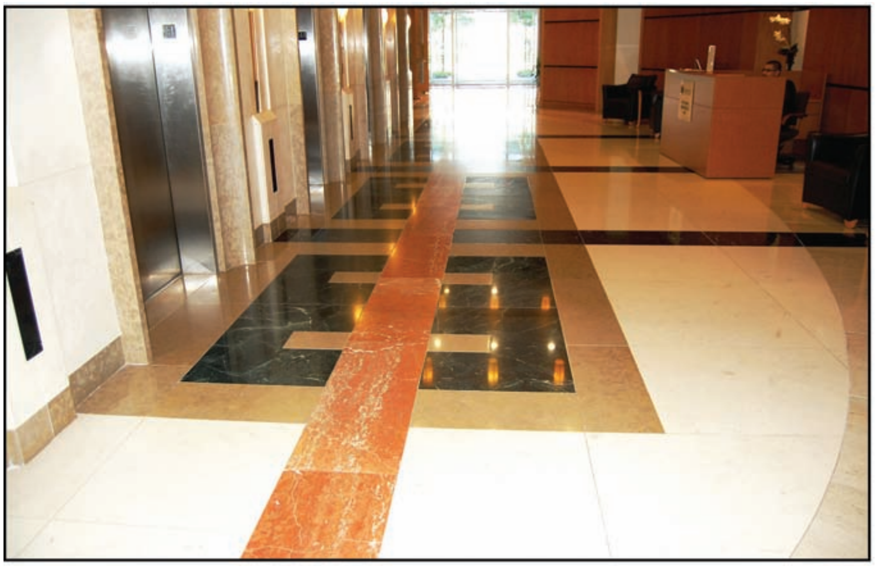


FIGURE 36.15 Natural stone panel flooring in the lobby of an office building. Important steps in the installation of this floor are shown in Figures 36.13 and 36.14.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. The two most common types of subfloor for floor coverings are
   - **a.** steel decking and wood plank.
   - **b.** concrete and steel.
   - **c.** concrete and wood panel.
   - **d.** wood light-frame and plywood panels.
   - **e.** carpet and vinyl flooring.
2. The vapor retarder below a concrete slab-on-ground should be of an extremely low permeability. This requirement is more important if the floor covering is polymer based.
   - **a.** True **b.** False
3. The coefficient of friction of a floor surface measures its
   - **a.** wear resistance.
   - **b.** resistance to mold and mildew.
   - **c.** cleanability.
   - **d.** slip resistance.
   - **e.** walking comfort.
4. For a ceramic tile floor covering on a wood subfloor
   - **a.** a hardboard underlayment is recommended.
   - **b.** an unsanded plywood underlayment is recommended.
   - **c.** a sanded plywood underlayment is recommended.
   - **d.** a cement or fiber-cement backer board underlayment is recommended.
   - **e.** (b) or (d).
5. The terms "stone panel and stone tile" are used interchangeably in building industry.
   - **a.** True **b.** False
6. A thick-bed mortar consists of
   - **a.** Portland cement, sand, and water.
   - **b.** Portland cement, lime, sand, and water.
   - **c.** lime, sand, and water.
   - **d.** lime, limestone powder, sand, and water.
   - **e.** none of the above.
7. For setting the ceramic tiles on the subfloor, the most commonly used mortar is thick-bed mortar.
   - **a.** True **b.** False
8. A thick-bed mortar is proprietary to the manufacturer, while a thin-bed mortar is generic.
   - **a.** True **b.** False
9. Stone panel flooring is laid on the subfloor using
   - **a.** the epoxy mortar.
   - **b.** the polymer-modified Portland cement mortar.
   - **c.** the thick-bed mortar.
   - **d.** the thin-bed mortar.
   - **e.** any one of the above depending on the type of stone.
10. A notched trowel
    - **a.** is used in laying grout.
    - **b.** is used in laying thick-bed mortar.
    - **c.** is used in laying thin-bed mortar.
    - **d.** all of the above.
    - **e.** is not used in laying floor coverings.
11. A rubber float
    - **a.** is used in laying grout.
    - **b.** is used in laying thick-bed mortar.
    - **c.** is used in laying thin-bed mortar.
    - **d.** all of the above.
    - **e.** is not used in laying floor coverings.
12. To ensure that the width of joints between ceramic or natural stone tiles are uniform, the installer uses
    - **a.** a laser beam.
    - **b.** steel ruler.
    - **c.** chalk lines.
    - **d.** 2 × 4 wood straight edge.
    - **e.** plastic spacers.

36.5 TERRAZZO FLOORING

Terrazzo floor covering is a cast-in-place, wet mix of stone aggregate chips of various sizes and a binder, which may be either Portland cement or an epoxy resin. The process of laying the mix is similar to the laying of concrete in a floor slab, that is, the mix is placed, floated, and finally troweled smooth (see Section 21.8). However, unlike concrete, the exposed surface is ground and polished after it cures and hardens, Figure 36.16(a). Grinding and polishing exposes the binding matrix and aggregates, thus revealing a speckled and colorful surface resembling that of polished granite, Figure 36.16(b).

The stone commonly used for the aggregate is marble, but granite and pieces of broken glass are also used. By combining various sizes and colors of the aggregate with the color of the binder and laying them to a predetermined layout pattern, a large variety of creative designs can be obtained. Because of the strength of the aggregate and the binder, terrazzo is one of the most durable floor coverings. It is the covering of choice in areas experiencing large traffic, such as the airport buildings, railway stations, and entrance lobbies and foyers of important buildings.

CEMENTITIOUS TERRAZZO—THICK-SET TERRAZZO

Although terrazzo may be laid on a wood subfloor, a concrete slab is the ideal subfloor for terrazzo. The traditional terrazzo floor consists of white Portland cement as the binder. Although the normal, gray-color Portland cement can be used (to reduce cost), white Portland cement has the advantage in that its color can be altered by mixing it with a pigment. The detail of terrazzo floor with Portland cement as the binder is shown in Figure 36.17. It comprises a mortar bed of Portland cement and sand ($1\frac{1}{4}$ in. to $1\frac{1}{2}$ in. thick) laid directly over the concrete slab and overlaid with a $\frac{1}{2}$-in.-thick terrazzo mix.

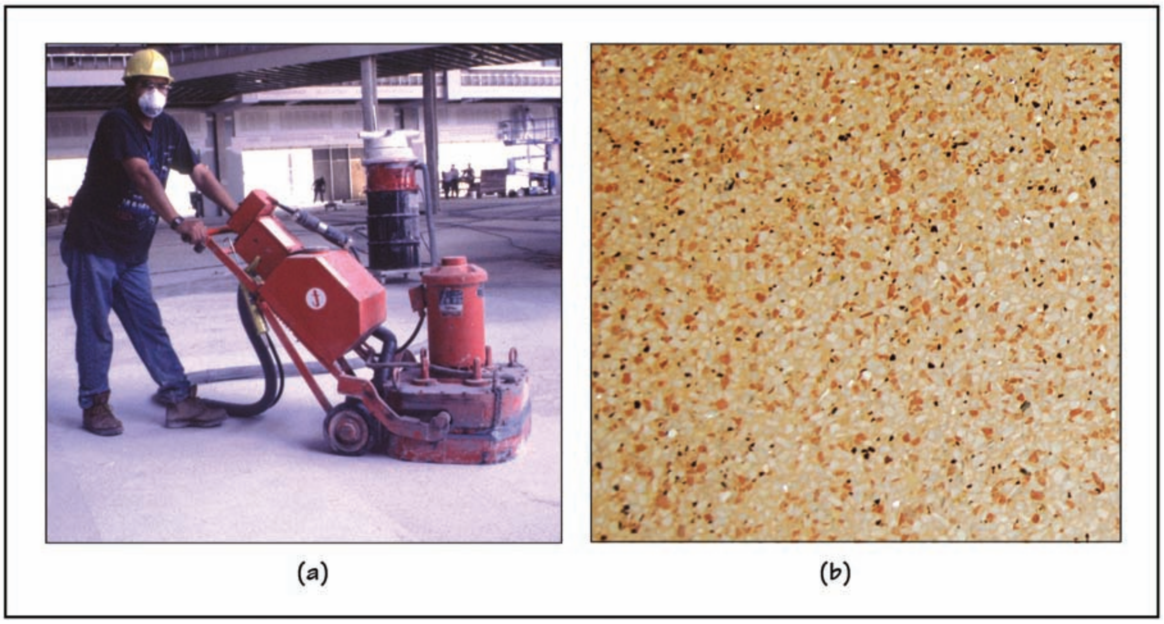


FIGURE 36.16 (**a**) A worker grinding the terrazzo floor. (**b**) Grinding and polishing the terrazzo floor exposes the aggregate and the binding matrix and the surface takes on a speckled appearance, much like that of polished granite.

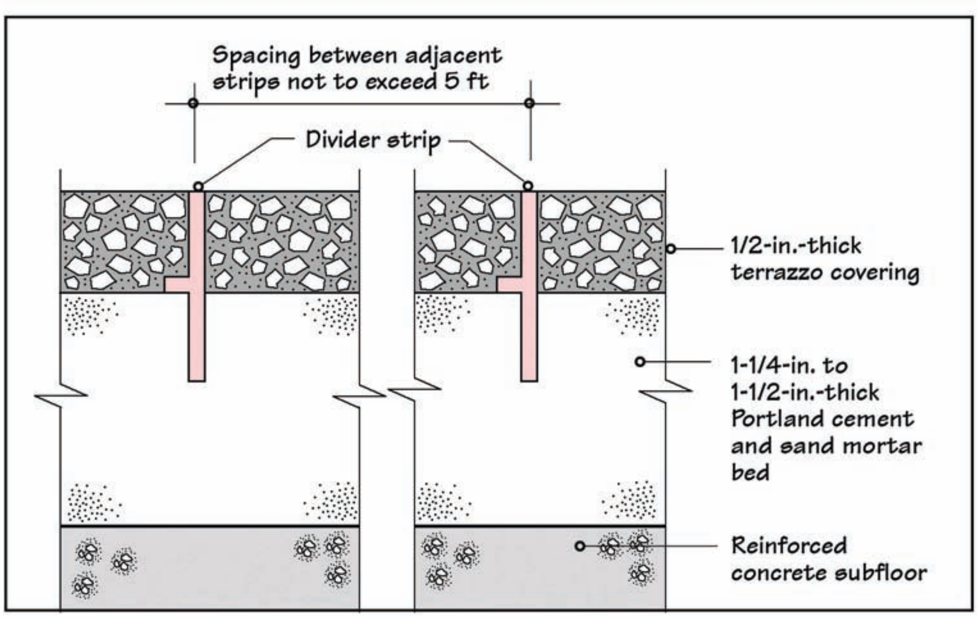

Spacing between adjacent strips not to exceed 5 ft
Divider strip
1/2-in.-thick terrazzo covering
1-1/4-in. to 1-1/2-in.-thick Portland cement and sand mortar bed
Reinforced concrete subfloor

FIGURE 36.17 A typical detail of a bonded cementitious terrazzo floor.

Because Portland cement shrinks as it cures, divider strips of brass, zinc, or plastics are used at spacing not exceeding 5 ft for crack control. They are inserted into the mortar bed before it begins to set. The placing of the terrazzo mix commences approximately 24 hours after laying the mortar bed. Apart from shrinkage control, the divider strips separate the floor into panels. By using mixes with white Portland cement, pigments of different colors, and different sizes of aggregates in different panels, an interesting floor layout can be created.

The terrazzo covering shown in Figure 36.17 is called *bonded cementitious terrazzo* because the mortar bed is bonded directly to the subfloor. A modification of this detail is shown in Figure 36.18. In this detail, a $\frac{1}{4}$-in. bed of sand and an isolation sheet separates the mortar bed from the subfloor. Referred to as *sand-cushion cementitious terrazzo*, it is used only in situations where the subfloor is subjected to excessive deflections or vibrations. The mortar bed is thicker than in the bonded cementitious terrazzo and wire mesh or metal lath reinforcement is provided within the mortar bed.

EPOXY TERRAZZO—THIN-SET TERRAZZO

Although Portland cement as a binder is still used for reasons mentioned in the following section, the advances in synthetic binders have largely replaced it with epoxy resins. Epoxy resin terrazzo mix is stronger than Portland cement–based mix, more flexible and does not crack on curing. Therefore, an epoxy terrazzo can be laid directly on the concrete subfloor

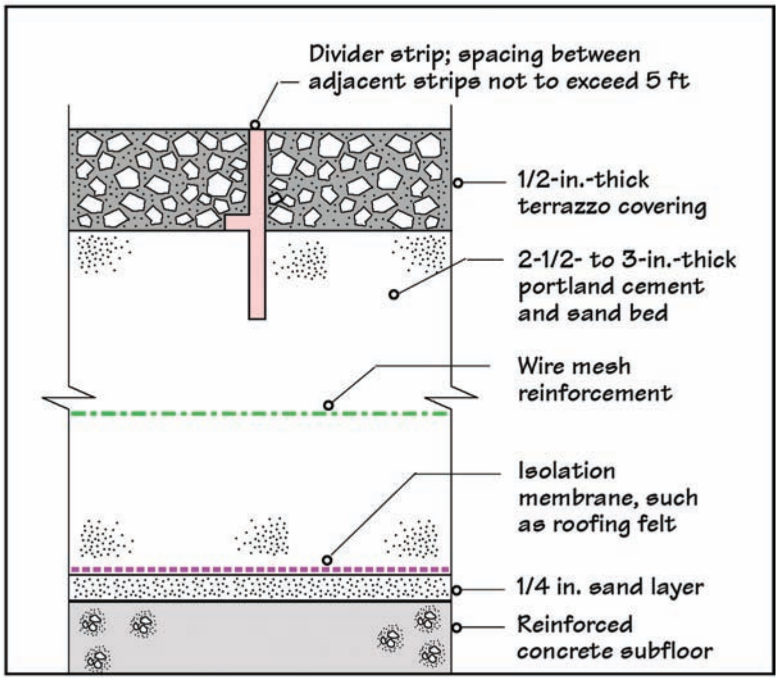

Divider strip; spacing between adjacent strips not to exceed 5 ft
1/2-in.-thick terrazzo covering
2-1/2- to 3-in.-thick portland cement and sand bed
Wire mesh reinforcement
Isolation membrane, such as roofing felt
1/4 in. sand layer
Reinforced concrete subfloor

FIGURE 36.18 A typical detail of sand-cushion cementitious terrazzo floor.

to a thickness not exceeding $\frac{3}{8}$ in. and does not need divider strips. The strips are, however used at floor terminations and transitions (to other floor coverings). They are also needed to separate mixes of different colors. Unlike cementitious terrazzo in which the strips are inserted into the mortar bed, the strips in epoxy terrazzo are epoxy-adhered to the subfloor, Figure 36.19(a). A typical detail of epoxy terrazzo, also called *thin-set terrazzo*, is shown in Figure 36.19(b).

Because the divider strips are only about $\frac{3}{8}$ in. deep, they can be straight or bent into curves, giving linear and curvilinear floor layout patterns that are unique to terrazzo. A typical contemporary epoxy terrazzo floor is shown in Figure 36.20.

LIMITATIONS OF EPOXY TERRAZZO

Being a polymeric compound, epoxy terrazzo is vapor impermeable (unbreathable), that is, it does not allow moisture from the subfloor to pass through—unlike in cementitious terrazzo—which is vapor permeable. Any vapor trapped between the terrazzo finish and the subfloor will delaminate the terrazzo over time. Therefore, when epoxy terrazzo is used on a slab-on-ground, the vapor retarder below the slab should have extremely low vapor permeability. Additionally, before laying the terrazzo mix, the concrete slab should be checked to ensure that it is dry, see margin note in Section 36.1.

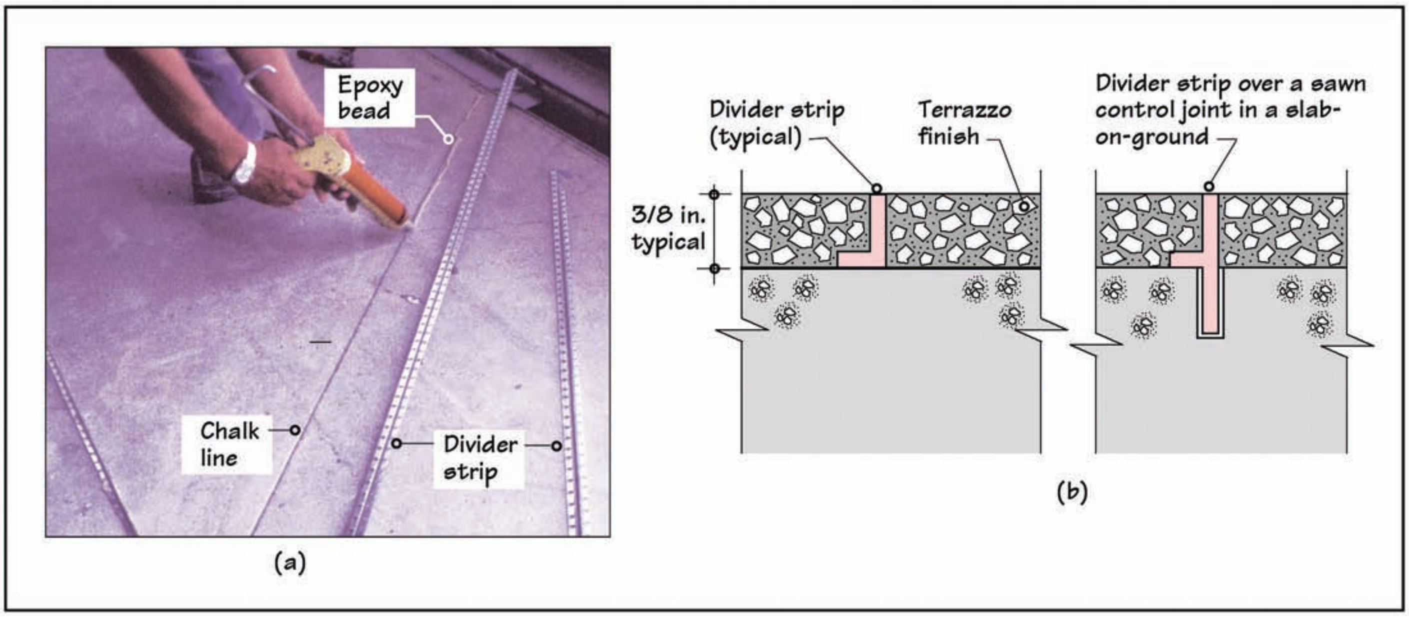

Epoxy bead
Chalk line
Divider strip
(a)
Divider strip (typical)
Terrazzo finish
Divider strip over a sawn control joint in a slab-on-ground
3/8 in. typical
(b)

FIGURE 36.19 **(a)** A worker laying a bead of adhesive along a chalk line in preparation for adhering the divider strip for the epoxy terrazzo floor. **(b)** Detail of divider strips used in an epoxy terrazzo floor.

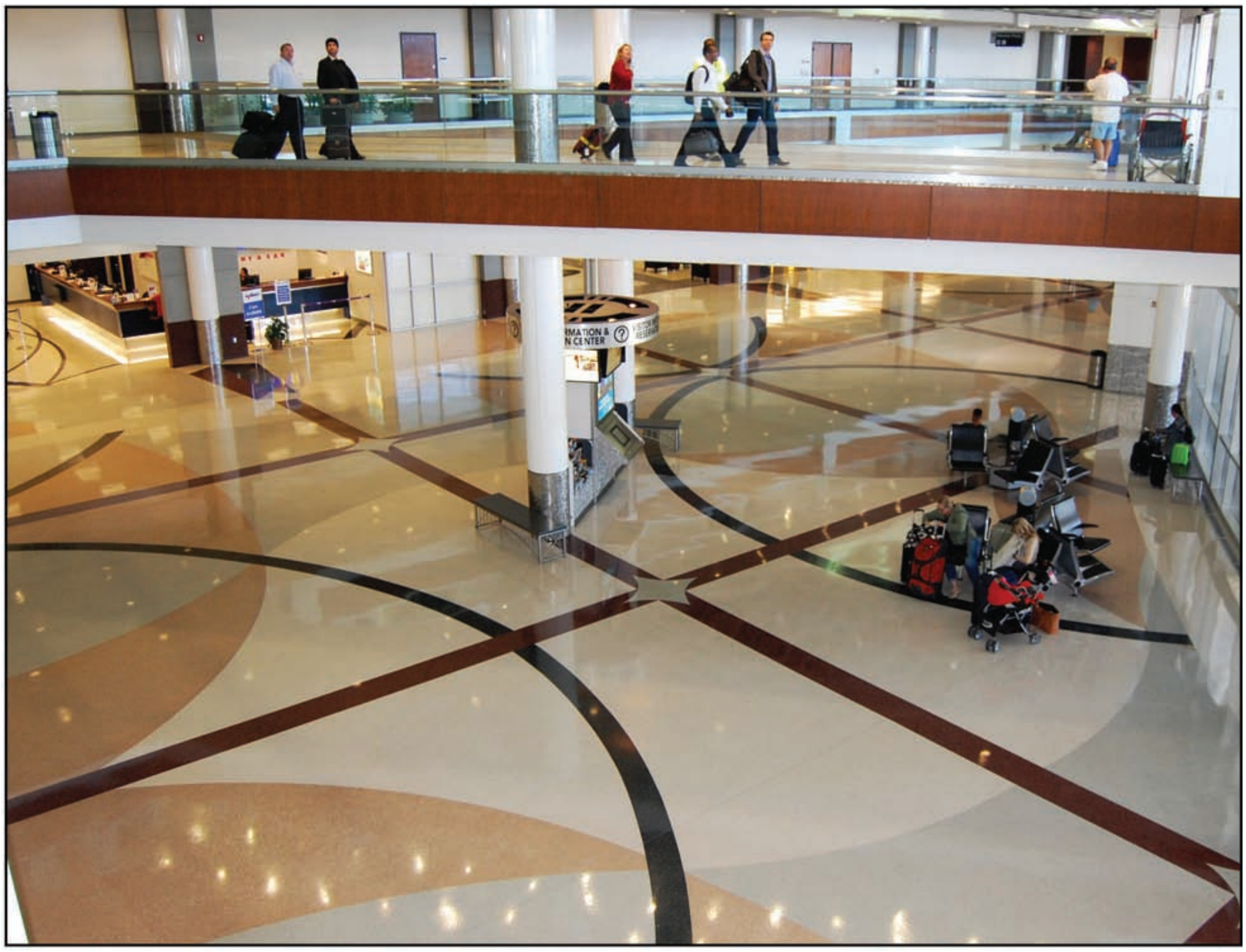


FIGURE 36.20 An ornate layout of terrazzo floor in a high-traffic space. The variety of colors and complex curvilinear patterns are unique to terrazzo. The white spots in this image are reflections of overhead lighting, showing the glossy nature of a terrazzo floor.

Another limitation of epoxy terrazzo is that, like all polymers, it deteriorates in strength when exposed to the Sun's ultraviolet rays. Hence, epoxy terrazzo cannot be used on outdoor surfaces.

36.6 CARPET FLOORING

Carpet is a commonly used flooring material. It is soft and warm underfoot, available in a wide range of colors and design patterns, quickly installed on both concrete and wood subfloors, relatively inexpensive, and absorbs impact noise from foot traffic. It has several drawbacks as well, the most significant being its combustibility and propensity to collect dust and muck from under the shoes.

Some other drawbacks of a carpet floor include its susceptibility to stain and lack of durability relative to other floor coverings. Even carpets with stain resistant treatment will stain somewhat and even the more expensive carpets with good maintenance protocol will need replacement after 15 to 20 years. The adverse impact on air quality from the adhesives used in carpets is also a concern, as discussed at the end of this section. In most contemporary buildings in North America, carpet floor is generally limited to bedrooms of single-family and multifamily dwellings, private offices, meeting rooms, aisle areas of cinemas, music halls, and auditoriums.

Two basic types of carpet are rolled goods and tiles. Rolled goods, also called broadloom, dominates the carpet industry and is primarily used in wall-to-wall applications. Rolls are typically 6 ft or 12 ft wide, and the seams are easily joined to become invisible. Carpet tiles allow the replacement of individual tiles. They are generally recommended for floors which may get damaged or stained frequently, such as in kindergartens or nursery schools.

Anatomy of a Broadloom (Wall-to-Wall) Carpet Floor

A typical broadloom carpeted floor consists of carpet and felt pad. The pad is laid directly over the subfloor and the carpet is laid over the pad without any adhesives (except with glued-down carpets). As previously mentioned, the subfloor for carpet can be either wood

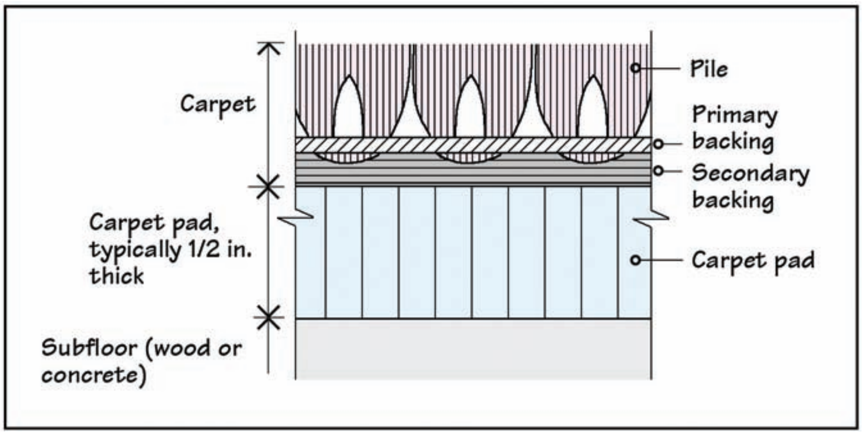

Carpet
Carpet pad, typically 1/2 in. thick
Subfloor (wood or concrete)
Pile
Primary backing
Secondary backing
Carpet pad

FIGURE 36.21 Anatomy of a carpet floor.

(OSB or plywood) or concrete, Figure 36.21. A felt pad adds to cushioning provided by the carpet and increases its performance and durability. Urethane foam ($\frac{1}{2}$ in. thick) is most commonly used for pads. It is available in various densities (6 to 20 pounds per cubic foot), is durable, and not affected by moisture—a property particularly important for a carpet laid on a concrete slab-on-ground. A denser pad is more durable but less soft.

A typical carpet has three components: (i) pile, the fibrous, top part of the carpet, (ii) primary backing, and (iii) secondary backing, as shown in Figure 36.21.

PILE FIBER AND YARN

Like a garment, a carpet pile is made from yarn, which is spun from fibers. Therefore, the type of fibers used in the yarn is the most important determinant of the carpet's performance and appearance. The traditional carpet yarn is spun from wool. Wool fibers do not hold surface dirt, do not soil readily, and are naturally flame resistant, but are the most expensive fibers. Therefore, wool is generally used only in rugs and high-end carpets.

Most contemporary carpets use yarn made from synthetic fibers—nylon, polypropylene, and polyester. Of these, nylon has about 75% market share because it offers the best performance characteristics. Nylon fibers are abrasion resistant, highly resilient (i.e., resist crushing and matting), accept dyes well, and are easier to clean. Polypropylene and polyester fibers are good in other performance characteristics, but have low resilience and crushing strength. They are also less expensive. Carpets with polypropylene and polyester fibers are used in low-traffic situations, such as dwellings.

PILE CONSTRUCTION

The pile is attached to primary backing in two different ways: tufting and fusion bonding, Figure 36.22. In a tufted carpet, loops of yarn are sewn through primary backing and locked in place with latex adhesive. The primary backing is generally woven polypropylene.

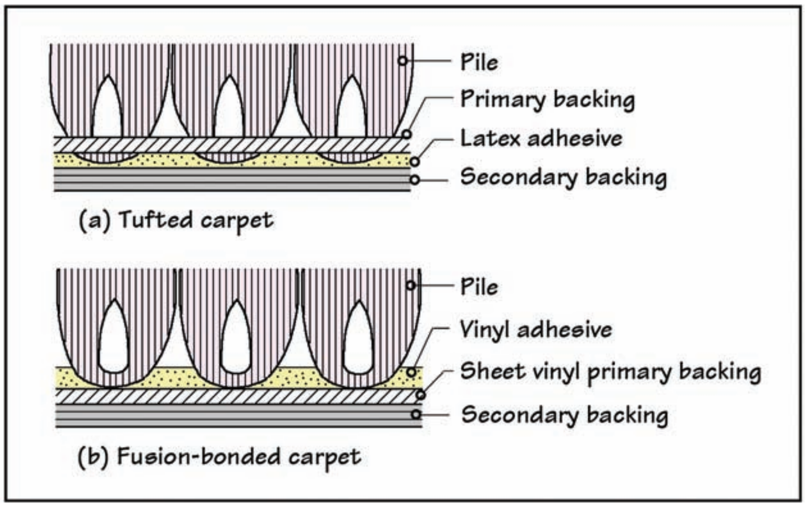
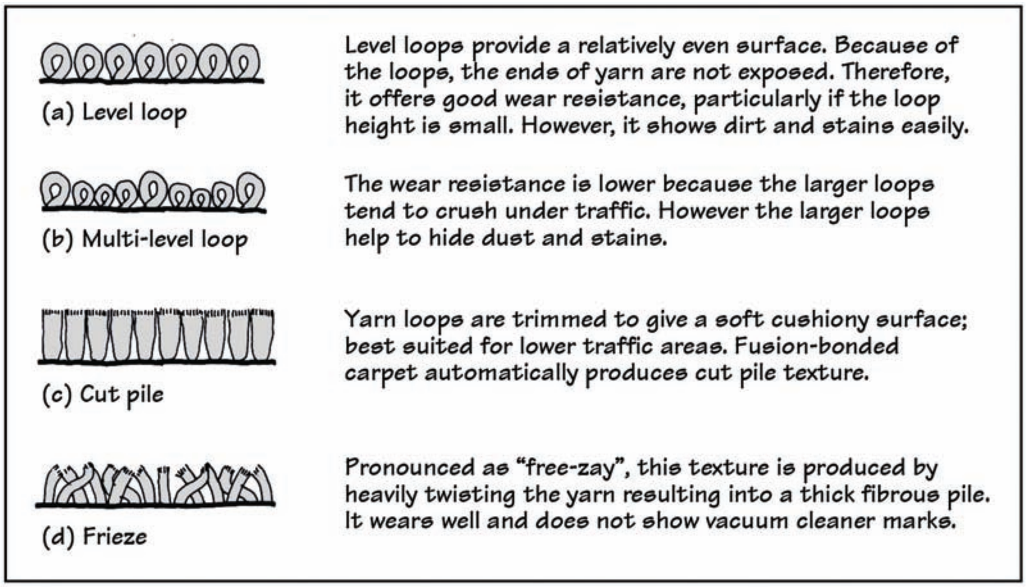

Pile
Primary backing
Latex adhesive
Secondary backing
(a) Tufted carpet
Pile
Vinyl adhesive
Sheet vinyl primary backing
Secondary backing
(b) Fusion-bonded carpet

FIGURE 36.22 Two commonly used compositions of carpet. In a tufted carpet, the yarn of the pile is sewn through the primary backing. In a fusion-bonded carpet, the pile is adhesive bonded to primary backing. Note that a fusion-bonded carpet yields cut-pile texture. A tufted carpet will provide several other textures (see Figure 36.23).



Level loops provide a relatively even surface. Because of the loops, the ends of yarn are not exposed. Therefore, it offers good wear resistance, particularly if the loop height is small. However, it shows dirt and stains easily.

The wear resistance is lower because the larger loops tend to crush under traffic. However the larger loops help to hide dust and stains.

Yarn loops are trimmed to give a soft cushiony surface; best suited for lower traffic areas. Fusion-bonded carpet automatically produces cut pile texture.

Pronounced as "free-zay", this texture is produced by heavily twisting the yarn resulting into a thick fibrous pile. It wears well and does not show vacuum cleaner marks.

FIGURE 36.23 Commonly used pile textures.

In a fusion-bonded carpet, the yarn is embedded between two parallel, adhesive-coated sheets of backing. This sandwiched assembly is then split through the middle, producing two sheets of pile. The texture of the pile produced through fusion bonding is a *cut pile* texture because of the splitting process. A fusion-bonded pile is denser than a tufted pile. A third, less used method, of making a pile is weaving, resulting in a woven pile.

The secondary backing in a pile provides additional strength to the carpet and is adhered to primary backing with a latex coating. Like the primary backing, the material commonly used for secondary backing is also woven polypropylene.

SURFACE TEXTURE OF PILE

A carpet pile can have several different textures, which impact not only the carpet's aesthetics, but also its performance. The most common textures are: level loop pile, multilevel loop pile, cut pile, and frieze pile. They are graphically shown in Figure 36.23, which also provides a brief description of their performance characteristics.

PILE DENSITY—AN IMPORTANT METRIC OF CARPET PERFORMANCE

Pile density is one of the most important performance metrics of a carpet because it is related directly to the carpet's durability. It is a measure of the compactness of the pile yarn and ranges from 1,000 to 6,000 in numerical value. It is defined as the weight of 1 sq yd of pile yarn excluding the backing, called the *face weight*. It is expressed in terms of ounces per cubic yard (oz/cu yd). For example, let us calculate the pile density of 1 sq yd of $\frac{1}{2}$-in.-thick pile weighing 40 oz. Because $\frac{1}{2}$ in. $= \frac{1}{72}$ yd, the volume of 1 sq yd pile $= \frac{1}{72}$ cu yd. Therefore, pile density $= (40 \times 72) = 2{,}880$ oz/cu yd. We generally drop the units and simply state the pile density as 2,880. Thus, a formula commonly used to calculate pile density is:

$$\textit{Pile density} = \frac{36(\text{face weight})}{\text{pile height}}$$

In the above expression, face weight is in ounce and pile height is in inch. In addition to pile density, there are several other parameters that determine the performance of a carpet, such as gauge and pitch of carpet, and pile height.

FLAMMABILITY OF CARPET

Carpets are evaluated for flammability, as regulated by building codes. Flame spread is tested by the flooring radiant panel test, which determines a carpet's ability to spread fire. This is identified as the critical radiant flux (ASTM E-648 test). Another measure of the ability of a carpet to promulgate a flame from a small source, such as a match or cigarette, is determined from the pill test (see Section 7.8).

CARPETS AND INDOOR AIR QUALITY

The emission of volatile organic compounds (VOCs) from the adhesives used in carpets and carpet pads has long been a concern because it affects the indoor air quality (IAQ),

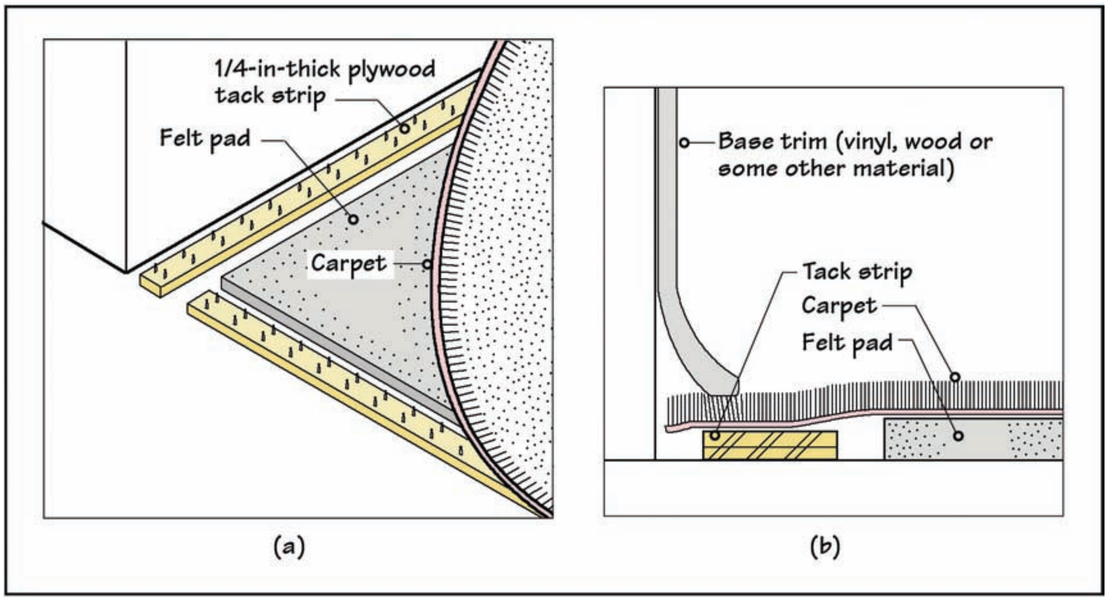

1/4-in-thick plywood tack strip
Felt pad
Carpet
(a)
Base trim (vinyl, wood or some other material)
Tack strip
Carpet
Felt pad
(b)

FIGURE 36.24 **(a)** Installation of carpet using tack strips. Tack strips are nailed to an OSB or plywood subfloor and adhered to a concrete subfloor. **(b)** At room boundaries, the carpet is tucked under a base trim.

particularly with glued-down installations. The Carpet and Rug Institute (CRI) provides guidelines for installation of carpets to reduce VOCs, such as leaving the windows open during and after installation, operating the mechanical ventilation system with maximum outdoor air for 48–72 hours, and considering being out of the premises during the above period. In addition, the use of carpet and carpet pads carrying CRI's Green Label Plus assures lowest possible VOC emissions (see Section 10.9).

INSTALLATION OF BROADLOOM CARPET

Two methods are used for installing broadloom (wall-to-wall) carpet. The most commonly used method is the stretch-in *method*. In this method, the carpet is placed over a pad, and is stretched (placed in tension) and then securely hooked to tack strips at the perimeter of the room, Figure 36.24(a). Power stretchers are used for stretching the carpet.

A tack strip is a strip of plywood, typically $\frac{1}{4}$ in. thick and $1\frac{1}{2}$ in. wide, and contains small spikes along its length, which are slightly bent toward the wall side. After the carpet has been installed, the edges of the carpet are tucked under a base trim (wood, vinyl, or some other material), Figure 36.24(b).

The stretch-in method is generally used for areas that experience low traffic or where the distance between tack strips is not too large. If used in heavy or extra-heavy traffic areas, the carpet and the cushion will tend to "travel" in the direction of the dominant foot traffic and will become wrinkled or detached from the nail strips. In such areas, the direct glue-down *method*, using a compatible adhesive, is used to attach the carpet to the subfloor.

36.7 WOOD FLOORING

Wood and engineered wood products are discussed in Chapters 13 and 14, and much of the same information also applies to wood flooring. Wood flooring is valued in residential applications for its warmth and beauty. It is also used extensively for athletic floors, such as basketball, volleyball, and racquetball courts, as well as for theatre and dance floors, where durability, hardness, and resiliency are highly desired. Although most wood species can be fabricated for wood flooring, all of them are not equal in performance.

CHARACTERISTICS OF WOOD FLOORING

Virtually any hardwood or softwood species can be used for wood flooring. However, some species may not be easily available, and some cannot be suitably finished for wood flooring applications. The characteristics of most importance for evaluating wood flooring are species, appearance (including grain, texture, and color), cut, durability, dimensional stability, and ability to accept finishes.

Oak and maple are the most commonly used species in the United States. However, as many as 50 hardwood and softwood species are used, such as white ash, American and red beech, yellow birch, hickory, walnut, bamboo, Brazilian walnut (known as *ipe*), and southern pine.

Generally, wood floorings are classified as either solid wood flooring or engineered wood flooring. As the name implies, in solid wood flooring the same wood species is used throughout the entire piece. It is susceptible to changes in size due to moisture content. It can be flat sawn or quarter sawn, and is available in different appearance grades.

Like plywood, engineered wood flooring is a combination of a surface veneer, usually a hardwood, which is laminated to one or more plies of a wood veneer from a less expensive wood species that provides dimensional stability and added strength.

Either material can be fabricated into a variety of shapes and sizes. They are categorized into three groups: strips (usually $1\frac{1}{2}$ to $2\frac{1}{4}$ in. in width and random in length), planks (usually 3 in. to 8 in. in width and random in length), and parquet (a patterned floor, which can be strips, planks, blocks, or square tiles).

The typical profile for wood flooring is known as a tongue-and-groove (T&G) profile, Figure 36.25. This allows for accurate alignment during installation and—because of its uniformity—tight, level joints. The thickness of solid wood flooring varies according to usage: approximately $\frac{5}{8}$ in. thick for light use; $\frac{3}{4}$ in. thick for normal use; and 1 in. to $1\frac{1}{2}$ in. thick for heavy use.

Wood floorings are finished to protect the wood from dirt, abrasion, wear, oxidation, and moisture (to some extent). They can be finished by the manufacturer, resulting in higher-performing finishes than field-applied finish. When field finished, the floor is sanded, stained, sealed, and waxed. Wood flooring can be factory impregnated with an acrylic, which increases its density, hardness, and resistance to wear. Because the acrylic seals the wood from moisture, the wood's dimensional stability is greatly improved.

PHYSICAL PROPERTIES OF WOOD FLOORING

The two most important physical properties to consider for wood flooring are density and hardness. A wood species with a high density is required for wood flooring. Hardness is necessary to resist indentation and marring. The side hardness of the wood species ranges from 380 ft-lb for eastern white pine (softest) to 3,680 ft-lb (hardest) for Brazilian walnut (ipe).

The species of the wood used and its grade and cut are important considerations that affect the dimensional stability, durability, and appearance of wood flooring. Wood flooring used for athletic purposes should possess the physical properties of absorption of impact shock, ball rebound, deflection resistance, and control of surface friction. Hard maple is favored because it meets these requirements well.

INSTALLATION OF WOOD FLOORING

Unlike the other floor coverings discussed in this chapter, controlling the moisture content of wood flooring during fabrication and installation is imperative. Wood being a hygroscopic material is subject to swelling and shrinking. Controlling moisture content is more important for solid wood flooring than for engineered wood flooring. To control moisture, wood is kiln dried to establish a baseline of moisture content; then, during fabrication and installation, it should be protected from changes in moisture. It is common to place wood flooring in the place where it will be installed for some time before installation to allow it to acclimate to the temperature and relative humidity.

Another unique factor concerning wood flooring is that an expansion space is necessary around the perimeter of the room to accommodate the small amount of movement the flooring may encounter due to changes in temperature and relative humidity during the life of the installation.

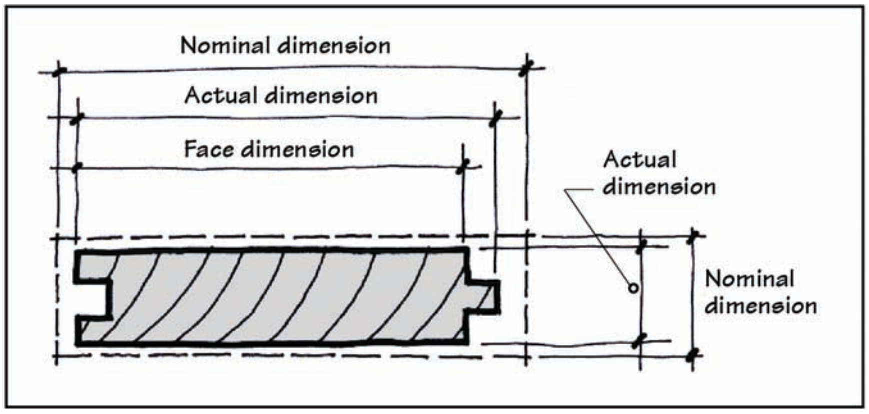


FIGURE 36.25 Solid wood flooring cross-sectional terminology.

There are several methods of installation for wood floorings. Historically, strips and planks were installed over wood sleepers. Today, strips, planks, and parquet can be installed over a plywood underlayment or directly to the subfloor. Nails, staples, and water-based adhesives are used to attach to wood subfloors, whereas adhesives are required for concrete.

A more sophisticated method of installation, in which an air space is established between the wood flooring and the substrate, is used for athletic wood flooring. Usually a vapor retarder is placed over the concrete substrate; then one of the following variety of support systems may be used:

- *Floating Systems:* Resilient materials such as neoprene, rubber, or polyvinyl chloride (PVC) sheets may be adhered to the substrate or a foam underlayment may be used to isolate the wood flooring from the subfloor.
- *Fixed-Wood-Sleeper Systems:* One or two layers of wood strips, at opposing directions, are attached to the subfloor.
- *Fixed-Metal Sleeper Systems:* As in the wood sleeper system, metal tubes, channels, or other shapes are used to create a grid on the subfloor.

36.8 RESILIENT FLOORING

Floor coverings made of sheet linoleum, vinyl (sheet or tile), cork (sheet or tile), and rubber (sheet or tile) are referred to as *resilient floor coverings*. They are the thinnest floor coverings used, and are supple enough to absorb impact sound, and resilient enough not to form permanent dents under moderate point loads, such as from furniture legs. The oldest form of resilient flooring is sheet linoleum, first introduced in the United Kingdom during mid-nineteenth century. Linoleum, however, has been overtaken by vinyl almost completely because vinyl covering is less expensive and performs better than linoleum. It is also available in tiles, in the form of solid vinyl tiles, but more commonly as *vinyl composition tiles* (VCT)—composed of vinyl and limestone and some other mineral ingredients.

Although cork and rubber floors are used, a vast majority of resilient floors today comprise sheet vinyl or VCT. Sheet vinyl covering is like wall-to-wall carpeting and VCT is like carpet tiles. VCT are easier to lay than sheet vinyl, and also more economical. Tiles are used where the joints are not objectionable. Sheet vinyl flooring is jointless. It is the floor covering of choice where joints are not permitted, and the floor may need to be mopped on a regular basis, such as in operating theatres and patient bedrooms. In such spaces, floor covering and base trims are continuous and jointless. The following discussion will focus on sheet vinyl covering.

COMPOSITION OF SHEET VINYL COVERING AND ITS LIMITATIONS

The primary material for sheet vinyl is polyvinyl chloride (PVC). Other materials used are mineral fibers for body and hardness, plasticizers for resilience, and colors for aesthetics. Vinyl sheets are bonded to a fiberglass backing for strength. Sheets are available in 6-ft-wide rolls and are generally (2 mm) $\frac{1}{12}$ in. thick. Vinyl sheets are also available with an integral cushioning layer. They are suppler, easier to lay, and less expensive but are not as durable as sheet vinyl without a cushioning layer, called *inlaid vinyl*. Cushioned vinyl is generally used in residential construction and is available in up to 12-ft-wide rolls.

Being a polymeric material, vinyl covering has the same limitations as an epoxy terrazzo floor, that is, UV degradation and a dry subfloor requirement (see "Limitations of Epoxy Terrazzo" in Section 36.5). If vinyl covering is used in rooms flooded with daylight, its degradation potential should be evaluated.

PREPARATION OF SUBFLOOR FOR SHEET VINYL COVERING

Because it is a thin covering, the subfloor surface below vinyl covering should be smooth. Any irregularities in the subfloor will telegraph through it and will eventually damage the floor. Therefore, if the subfloor is a concrete slab, high spots should be ground and the depressions filled with subfloor patching compound (usually a latex-modified Portland cement–based proprietary material), including the sawed joints in a concrete slab-on-ground, Figure 36.26. With an OSB or plywood subfloor, a $\frac{1}{4}$-in.-thick plywood underlayment with a fully sanded face is used with joints lightly butted together.

INSTALLATION OF SHEET VINYL COVERING

After the subfloor has been prepared as just described, it is cleaned of all dust and dirt in readiness for the application of the adhesive. Chalk lines are used to separate sheet vinyl

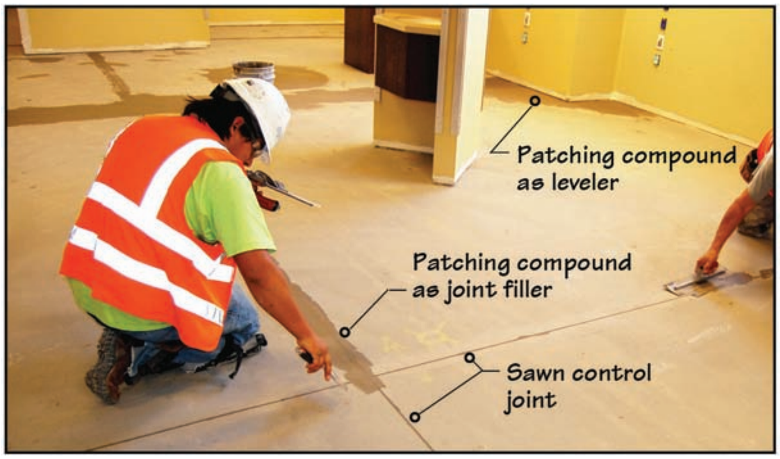


FIGURE 36.26 A concrete slab must be grinded smooth and any depressions must be leveled with patching compound and sanded after it has gained strength. In a concrete slab-on-ground, the control joints are filled with patching compound and similarly sanded.

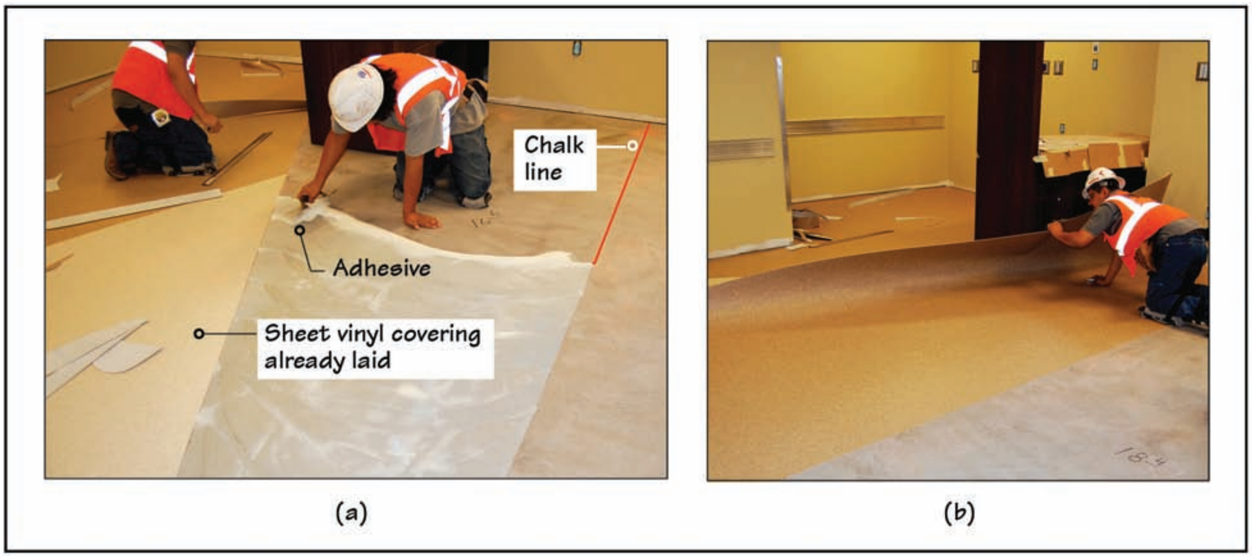


FIGURE 36.27 **(a)** Adhesive being applied with a notched trowel on a concrete subfloor. **(b)** A 6-ft-wide sheet vinyl roll being spread over the adhesive. The roll will be cut along the chalk line shown in (a) and also along the joint with the sheet already laid, see also Figure 36.29(a).

of one color or pattern from the other, and the adhesive is applied along chalk lines with a notched trowel, Figure 36.27. The vinyl roll is now laid over the adhesive and pressed down with a roller pin, Figure 36.28. Any overlap between this sheet and the one previously laid is cut off, Figure 36.29.

The seams between sheets are welded together by heating a vinyl bead (approximately $\frac{3}{16}$ in. diameter and of matching color) with a hot air welding equipment. This deposits the molten vinyl within the seams. After the molten vinyl has cooled down, the excess is scraped off, Figure 36.30. The result is a jointless floor with indistinguishable seams.

FLASH COVE BASE

The junction between the floor and the wall can be treated in the traditional way, that is, by using a base trim (typically of wood or vinyl), similar to the one shown in Figure 36.24(b). However, where a jointless transition from the floor to the wall is required to provide a

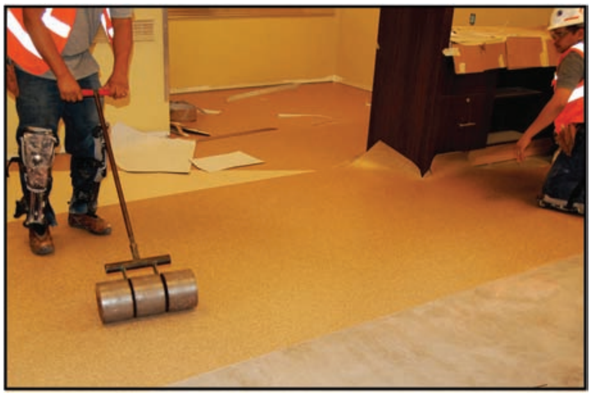


FIGURE 36.28 Vinyl sheet being pressed over the adhesive with a roller pin.

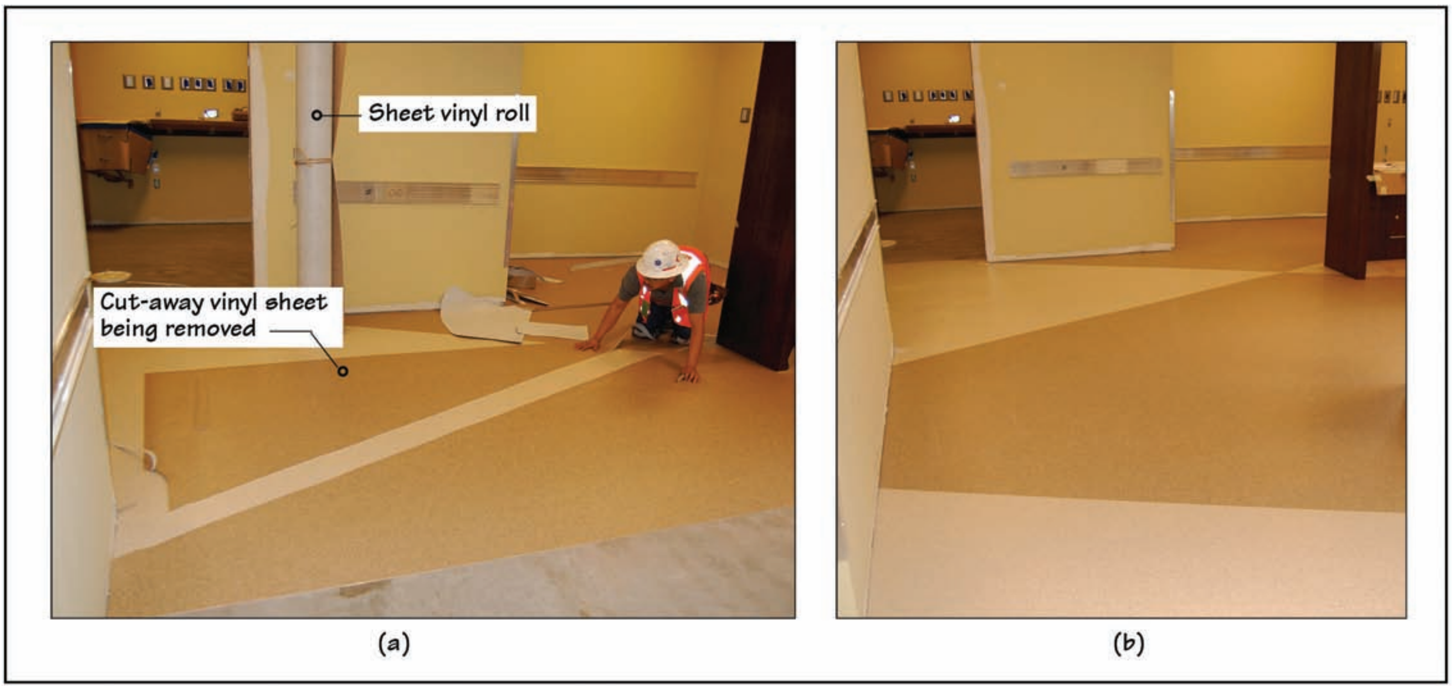


FIGURE 36.29 **(a)** Vinyl sheet has been cut away at the overlap between the previously laid sheet. **(b)** Partially completed sheet vinyl floor showing sheets of different colors laid according to a layout design.

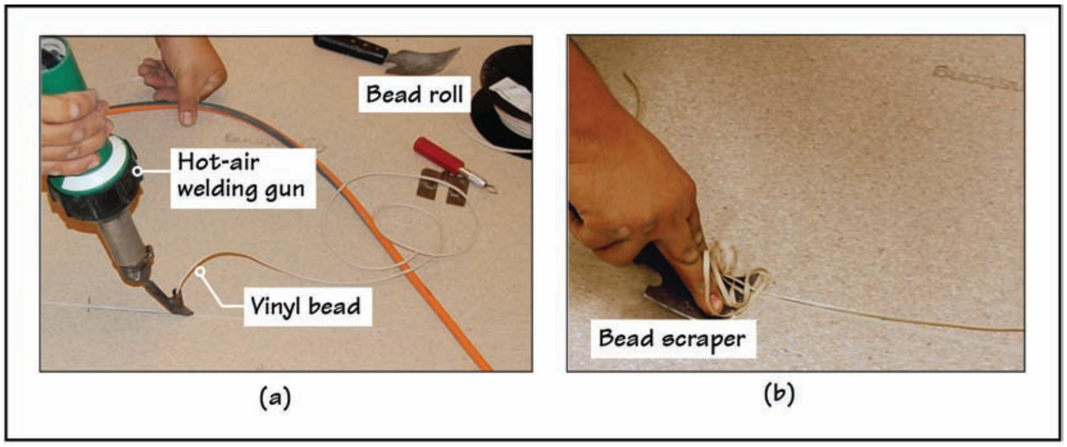


FIGURE 36.30 **(a)** Welding the seams between sheets with vinyl bead and a hot-air gun. **(b)** After welding, the projecting part of bead is scraped off to reveal a jointless floor in which the seams are indistinguishable from the vinyl covering.

hygienic floor, the sheet vinyl is extended from the floor into the wall to produce an integral base, known as a flash cove base, Figures 36.31(a) and (b).

This detail requires installing a rubber, wood, or vinyl cove strip at the floor-wall junction so that the transition of the vinyl sheet from the floor to the wall is smooth. Additionally, a metal or plastic cove trim is needed to terminate the sheet vinyl, Figures 36.31(b) and (c). The sheet vinyl is secured to the wall with an adhesive and inserted into the cove trim, Figure 36.31(d). To ensure a smooth transition and a good bond of sheet vinyl with the wall, the sheet vinyl is softened by heating it with a torch, Figure 36.31(e) and pressed in using a roller pin, Figure 36.31(f).

36.9 OTHER FLOOR-COVERING MATERIALS

The floor coverings described in the foregoing sections are those that are more commonly used in contemporary construction. There are several other coverings that are used for special purposes, such as resinous flooring, polished concrete, floors for gymnasiums and sports facilities, and elevated access flooring.

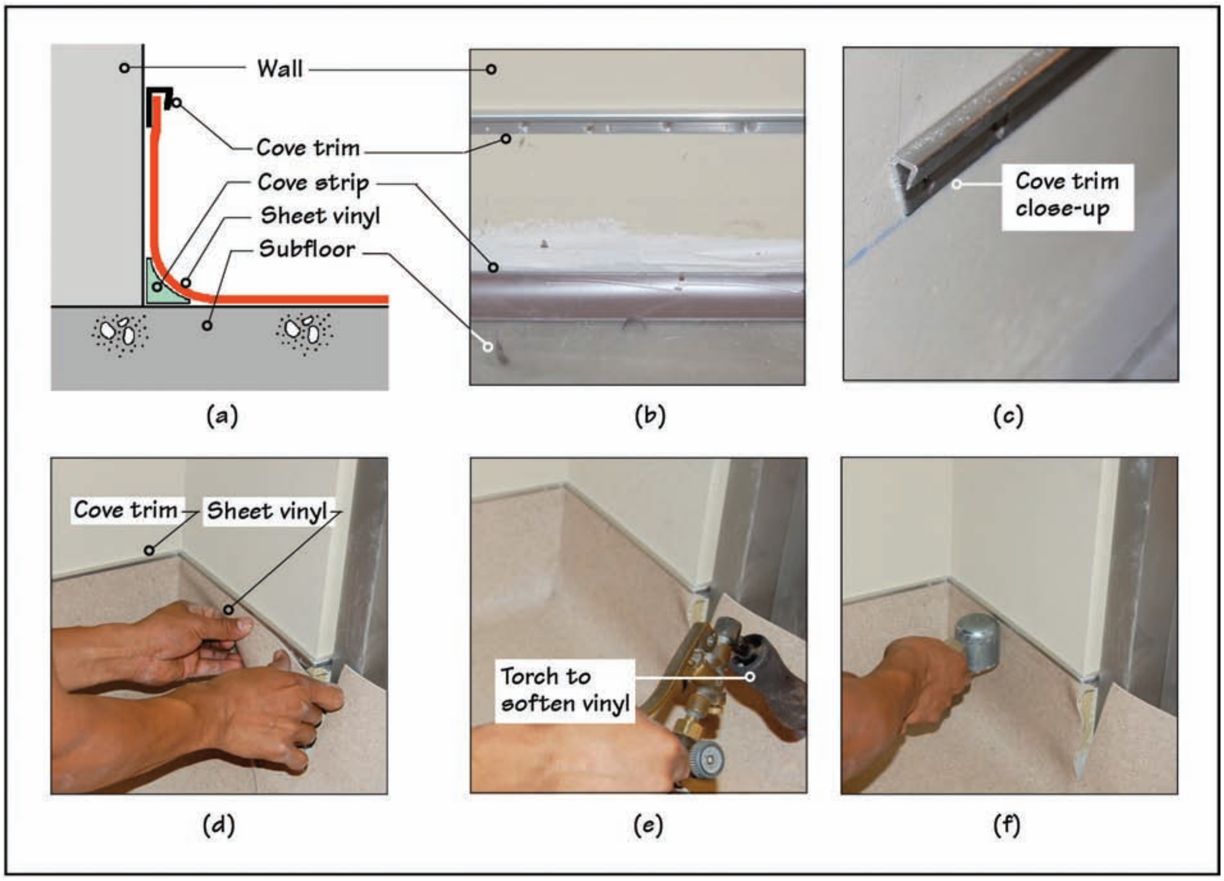


FIGURE 36.31 Steps in the installation of flash cove base.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

13. Terrazzo floor covering is like concrete in that it
- **a.** is a mix of binding agent and aggregate.
- **b.** is liquid when placed and cures hard.
- **c.** is saw-cut to control cracking.
- **d.** all of the above.
- **e.** (a) and (b).

14. A cementitious terrazzo floor covering is
- **a.** approximately $\frac{3}{4}$ in. thick.
- **b.** approximately $\frac{1}{2}$ in. thick.
- **c.** approximately $\frac{1}{4}$ in. thick.
- **d.** vapor permeable.
- **e.** (b) and (d).

15. A cementitious terrazzo floor covering
- **a.** requires divider strips at spacing not exceeding 3 ft.
- **b.** requires divider strips at spacing not exceeding 4 ft.
- **c.** requires divider strips at spacing not exceeding 5 ft.
- **d.** requires divider strips at spacing not exceeding 7 ft.
- **e.** does not require divider strips except at floor transitions and change of mix color and pattern.

16. A cementitious terrazzo mix is laid on a mortar bed, not directly on the subfloor.
- **a.** True
- **b.** False

17. An epoxy terrazzo mix is laid on a mortar bed, not directly on the subfloor.
- **a.** True
- **b.** False

18. An epoxy terrazzo floor covering
- **a.** requires divider strips at spacing not exceeding 3 ft.
- **b.** requires divider strips at spacing not exceeding 4 ft.
- **c.** requires divider strips at spacing not exceeding 5 ft.
- **d.** requires divider strips at spacing not exceeding 7 ft.
- **e.** does not require any divider strips except at floor transitions and change of mix color and pattern.

19. The carpet pad under a typical broadloom (wall-to-wall) carpet is typically 1 in. thick.
- **a.** True
- **b.** False

20. The texture of the pile in a fusion-bonded carpet is
- **a.** level loop pile.
- **b.** multilevel loop pile.
- **c.** cut pile.
- **d.** frieze pile.
- **e.** none of the above.

21. A typical broadloom carpet has two layers of backing.
- **a.** True
- **b.** False

22. To ensure that a broadloom (wall-to-wall) carpet stays in position and does not move, it is typically
- **a.** stretched and adhered to the subfloor along the room perimeter.
- **b.** stretched and tucked under the base trim and adhered to a 4-sq ft adhesive patch in the center of the room.
- **c.** stretched and hooked to tack strips along the room perimeter.
- **d.** stretched and hooked to tack strips along the room perimeter and adhered to a 4-sq ft adhesive patch in the center of the room.

23. The floor covering in which the base trim and the floor covering can be made jointless and continuous is
- **a.** marble panel floor.
- **b.** ceramic tile floor.
- **c.** epoxy terrazzo floor.
- **d.** cementitious terrazzo floor.
- **e.** sheet vinyl floor.

24. The seams between vinyl floor covering sheets are
- **a.** adhered together with a vinyl adhesive.
- **b.** adhered together with a urethane adhesive.
- **c.** adhered together with an epoxy resin.
- **d.** welded together with hot air.
- **e.** welded together with hot air and vinyl bead.

25. A flash cove base is used with
- **a.** sheet vinyl floor covering.
- **b.** vinyl tile floor covering.
- **c.** engineered wood floor covering.
- **d.** epoxy terrazzo floor covering.
- **e.** none of the above.

REVIEW QUESTIONS

1. Sketch in three dimensions a typical ceramic tile floor with a thin-bed mortar on: (a) concrete subfloor and (b) T&G OSB subfloor. Identify all components with labels.
2. Using sketches, explain the difference between the construction details of a natural stone tile floor and a natural stone panel floor.
3. Using sketches, explain the difference between the construction details of a cementitious terrazzo floor and an epoxy terrazzo floor.
4. Draw the detail showing how a broadloom carpet is anchored to the subfloor.
5. What type of floor covering would you recommend for the patient room in a hospital? Give reasons.
6. Explain how sheet vinyl floor covering is made seamless.
7. Draw the detail of a typical flash cove base used with sheet vinyl floor covering.

CHAPTER 37

Ceilings

CHAPTER OUTLINE

37.1 Selection Criteria for Ceiling Finish Materials

37.2 No Ceiling Finish—Exposed to the Plenum

37.3 Ceilings Attached to the Building Structure

37.4 Ceilings Suspended from the Building Structure

Ceilings can be brought low and articulated to create intimate spaces, or they can be pushed high to create awe-inspiring and dramatic spaces. They can be subtle in design or they can be highly expressive. They can impede sound or amplify it, and they can direct light by reflection or they can black it out. Whatever the requirements, ceilings can be used to accomplish varied design intents.

Historically, ceilings were the underside of the floor or roof structure above; the ceilings were either finished or the overhead structure was left exposed. The several architects of St. Peter's Cathedral in Rome, Figure 37.1, placed an exquisitely detailed dome at the center of the building and consequently created one of the most awe-inspiring buildings in the history of architecture. The ceiling of another awe-inspiring ancient building, the Pantheon in Rome, is coffered concrete that was originally covered in stucco.

Buildings today are far more complex and require space for their utilities (ductwork for the distribution of heat and cooling, electrical power, lighting, communications wiring, fire protection piping, etc.), as can be seen in Figure 37.2. In most buildings, the space overhead is the preferred location for many of these components; for that reason, ceiling systems were developed to conceal these from view. Today, a vast number of products and materials are available for this purpose.

In this chapter, we discuss the three primary strategies for constructing ceilings. First, and the simplest to accomplish, is the one in which the underside of the structure above forms the ceiling and any overhead mechanical and electrical components are left exposed. Second, the ceiling finish materials are attached directly to the overhead building structure to form a cover. Third, and most popular, ceiling finish materials are suspended from the overhead building structure. In the second and third strategies, the space between the ceiling and the floor or roof above is known as a *plenum*. When the ceiling is on the exterior of a building, it is called a *soffit*.

37.1 SELECTION CRITERIA FOR CEILING FINISH MATERIALS

Unless the ceiling is part of a fire-rated assembly (which is quite often the case), the reasons for the ceiling are discretionary. In residential buildings, the ceiling is attached directly to the

FIGURE 37.1 Ceiling played an important role in the interior design of buildings of antiquity, as shown in this highly ornate ceiling of St. Peter's Cathedral in Rome.

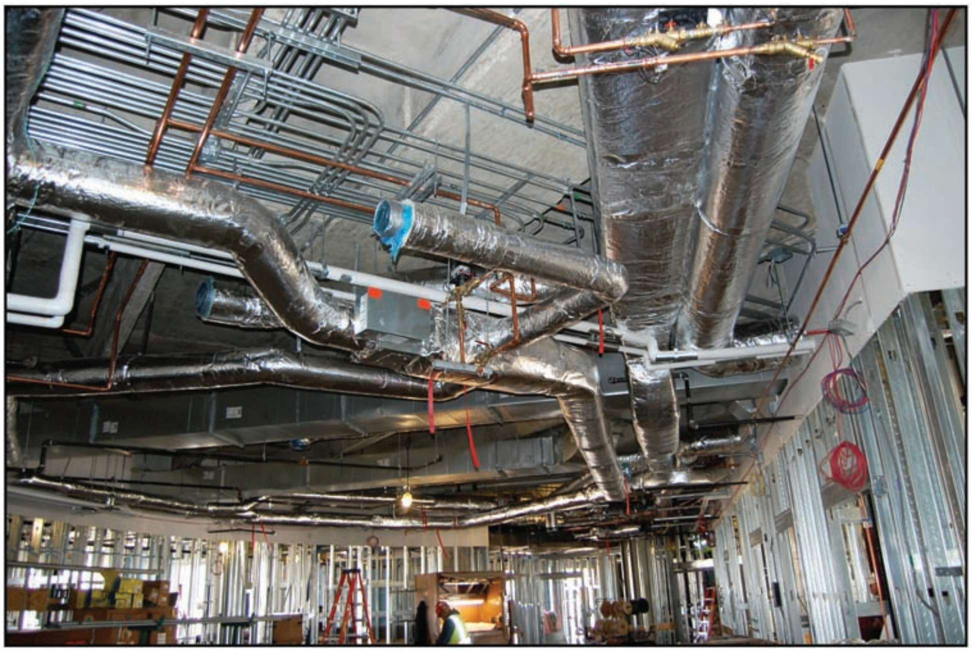


FIGURE 37.2 The complex arrangement of utility lines (HVAC ductwork, plumbing and water supply lines, electrical power and communication wiring, and other services) below the roof or floor of most contemporary buildings necessitate some kind of cover or screen below to conceal the arrangement from view. A suspended ceiling has, therefore, become a norm in most commercial interiors.

underside of the structure, and in most commercial buildings the suspended ceiling strategy is used. When ceilings are not included, the reason may be to reduce costs or to express the building utilities as part of the design. At other times, suspended ceilings can be used creatively to enhance the building's design.

There are several factors that must be considered when determining the appropriate ceiling type and finishes, and many of the principles discussed in Part I of the text apply. Factors unique to ceilings include the following:

- *Aesthetic Expectations:* Ceiling finish materials, heights, and profiles can create inviting environments and can influence the way light interacts with the building's interior. Unlike floors, ceilings are not limited to a single horizontal plane; they can be articulated at several elevations or can include vertical or sloped surfaces. Ceilings are used to introduce a sense of scale and proportion to an interior space. For example, if the area of the room is large, a high ceiling can create a grand space; however, if the area is small and the ceiling is high, the room may simply feel cavernous.

- *Concealing the Building's Utilities Overhead (mechanical and electrical equipment and components):* As previously discussed, the most common reason for a ceiling is to conceal the building's structure and overhead utilities, Figure 37.2.
- *Wind Loading:* Wind can impose an uplift load on the exterior soffit surface; therefore, wind-uplift resistance becomes an important consideration. In circumstances when large areas of the building enclosure are regularly opened to the exterior, wind can enter the building and exert a force on the ceilings.
- *Volume of Occupied Space:* Ceiling height is related directly to the volume of space required to be heated and cooled.
- *Humidity:* Ceilings adjacent to openings in exterior walls, especially major openings such as at a bank of frequently used doors, may be subjected to higher levels of humidity than the ceilings in the remainder of the building. Because many materials, when oriented horizontally, are vulnerable to sagging due to moisture absorption, the choice of materials must be carefully considered.
- *Flammability:* Building codes sometimes require ceilings to be resistant to fire propagation and spread.
- *Seismic Activity:* In seismically active areas, building codes require products, materials, and equipment installed overhead to resist the movements caused by an earthquake. During seismic activity, support structures and ceiling finish materials must not fall down, which would cause injuries to people trying to vacate the building.
- *Sound Absorption:* Ceiling finish materials and their method of application can help absorb sound generated within a room or space.
- *Sound Isolation:* In some situations, a ceiling assembly is used to help isolate sound from the overhead floor or ceiling. (See the discussion of impact isolation class, IIC, in Chapter 8).
- *Sustainability:* Many ceiling products contain recycled content and can make contributions to sustainability goals.
- *Antimicrobial Resistance:* In addition to normal maintenance, some applications may require ceilings to be resistant to bacterial growth and mold and mildew development.
- *Light Reflectance:* Ceilings can be used to reflect and/or diffuse light from other sources in order to distribute it uniformly throughout a space. Sometimes certain ceiling finish materials are selected—specifically to give the space a brighter appearance because indirect lighting is the preferred lighting source. This is also an important consideration when daylighting of an interior space is part of the design.
- *Maintenance:* Some occupancies, such as healthcare facilities, require ceiling finishes that can be regularly cleaned and scrubbed to remove possible contaminants. Other occupancies may require ceilings to resist soiling, scratching, and impact.

37.2 NO CEILING FINISH—EXPOSED TO THE PLENUM

One method of treating an interior space is not to have a ceiling, but rather to expose the building structure and utilities. Although this may seem simple, it requires careful design, detailing, and coordination of all exposed elements to produce a satisfactory result, Figure 37.3. This approach can make it easier to access certain elements for routine maintenance.

37.3 CEILINGS ATTACHED TO THE BUILDING STRUCTURE

In most residential buildings and some light-commercial buildings, lightweight ceiling finish materials are attached directly to the building structure. This is the most economical approach in residential applications, especially when there are few mechanical, plumbing, or electrical systems to be accommodated within the plenum. The most important consideration for this type of ceiling is that the underside of the building structure be specifically designed and located to provide surfaces for attaching the finished ceiling. Ceilings attached directly to the building structure do not usually require another structure, as is needed for suspended ceilings.

The most common material attached to the building structure is gypsum board. It is either nailed to the underside of the wood framing, or screwed to light-gauge steel framing (as at the underside of ceiling framing in Figure 20.3). The gypsum board is subsequently taped, bedded, textured, and painted. In addition, acoustical tiles can be attached with adhesive to the gypsum board finish.

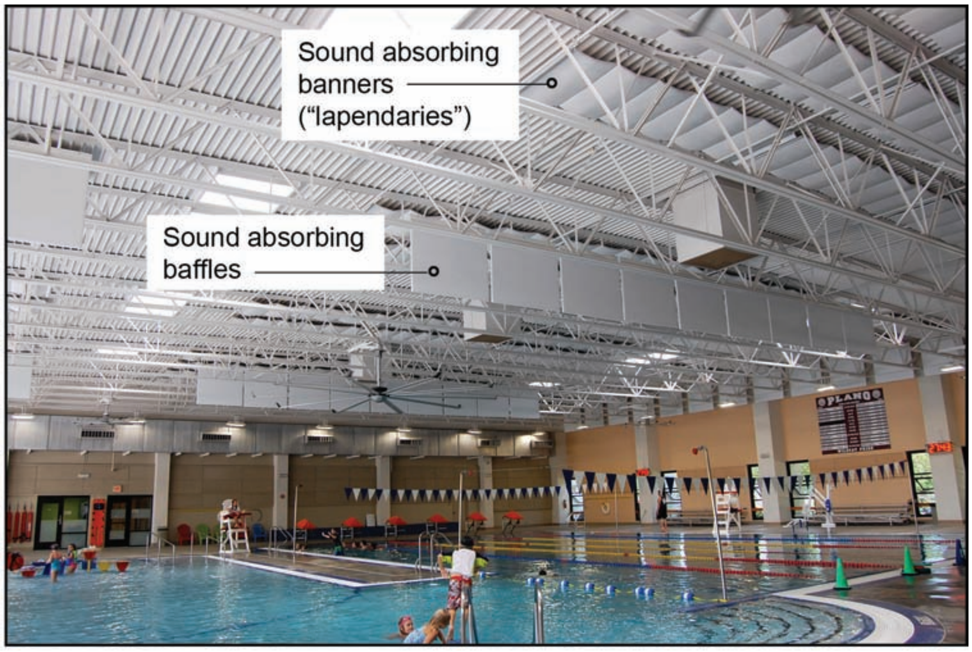


FIGURE 37.3 In many contemporary buildings, it becomes architecturally necessary to expose rather than conceal the overhead structural system and utility lines, as shown in this swimming pool interior. Here, the ceiling space has been used to absorb sound using acoustical baffles and banners, which would not have been possible using the conventional (planar) suspended ceiling.

PRACTICE QUIZ

Each question has only one correct answer. Select the choice that best answers the question.

1. All ceilings are formed by suspending a lightweight material from the underside of the structure to provide the interior finish.
   - **a.** True
   - **b.** False
2. The most common reason for a ceiling is to
   - **a.** control heat and humidity.
   - **b.** provide a sculpted or multilevel surface overhead.
   - **c.** reflect light.
   - **d.** conceal the building structure and overhead utilities.
   - **e.** isolate sound.
3. Antimicrobial ceiling materials are most likely to be used in a
   - **a.** university classroom.
   - **b.** hospital or medical laboratory.
   - **c.** department store.
   - **d.** pharmacy.
   - **e.** warehouse.
4. In a building where no ceiling is provided and the structure and utilities are exposed,
   - **a.** mechanical and electrical subcontractors are allowed easy access and freedom of choice in locating their work.
   - **b.** all systems must be carefully designed.
   - **c.** on-site coordination of construction is critical.
   - **d.** all of the above.
   - **e.** (b) and (c).
5. The ceiling provides an excellent opportunity to modulate natural and artificial light.
   - **a.** True
   - **b.** False

37.4 CEILINGS SUSPENDED FROM THE BUILDING STRUCTURE

By far the most common ceiling in commercial buildings is one that is suspended from the building structure overhead.

PRINCIPLES OF CEILING SUSPENSION SYSTEMS

A suspended ceiling system is a relatively simple concept. A very lightweight metal grid structure is suspended from the building's overhead structure to provide support for the ceiling finish products as well as to establish the ceiling height. This grid structure consists of main runners, suspended from above by steel wire, and interconnecting cross runners spaced uniformly to support the ceiling finish products.

There are three types of metal suspension systems, Figure 37.4. The type of suspension system used for a particular application depends on the structural requirements to support the ceiling finish products and other components that will be mounted on or attached to the grid structure, Table 37.1.

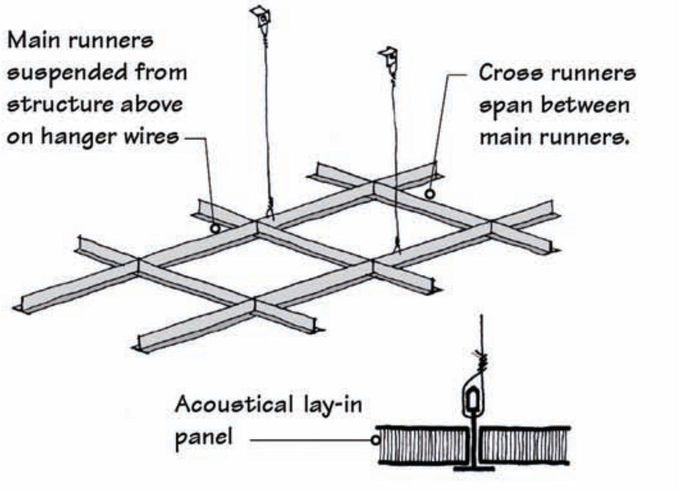
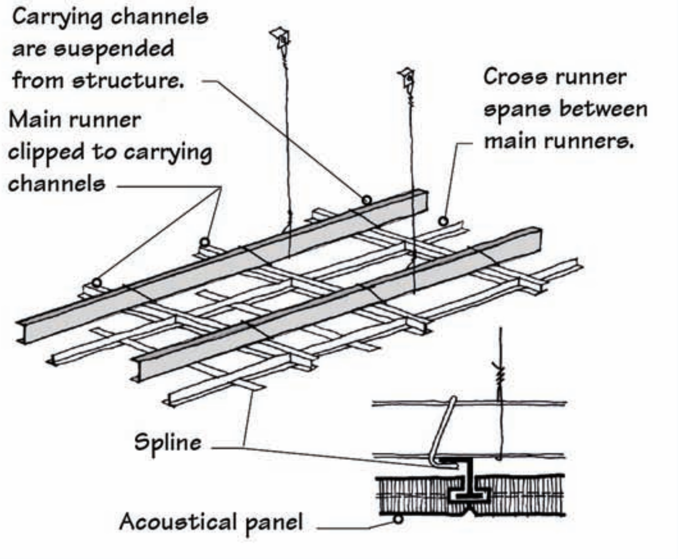
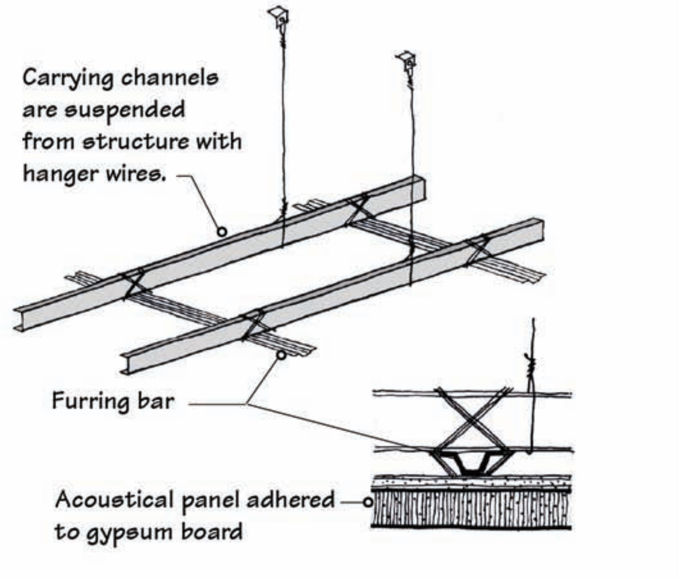
DIRECT-HUNG SUSPENSION SYSTEM	 Main runners suspended from structure above on hanger wires Cross runners span between main runners. Acoustical lay-in panel	Steel hanger wires are attached to the underside of the structure above at the required spacing with the ends hanging longer than will be necessary. The hanger wires are looped through the holes in the main runners and tied. Cross runners are snapped into and interlocked with the main runners. Acoustical lay-in panels are laid in each opening to create the finished ceiling.
INDIRECT-HUNG SUSPENSION SYSTEM	 Carrying channels are suspended from structure. Main runner clipped to carrying channels Cross runner spans between main runners. Spline Acoustical panel	Steel hanger wires are attached to the underside of the structure above at the required spacing with the ends hanging longer than will be necessary. The hanger wires are looped around the carrying channels and tied. Main runners are attached to the carrying channels using wire clips. Cross runners are snapped into and interlocked with the main runners. Concealed-spine acoustical panels are installed on the cross-runners and splines are used to frame the panels and distribute the load to the cross-runners.
FURRING BAR SUSPENSION SYSTEM	 Carrying channels are suspended from structure with hanger wires. Furring bar Acoustical panel adhered to gypsum board	Steel hanger wires are attached to the underside of the structure above at the required spacing with the ends hanging longer than will be necessary. The hanger wires are looped around the carrying channels and tied. Furring bars are attached to carrying channels by looping around the intersection several times with tie wire. Gypsum board is screw attached to the furring bar and then acoustical panels (or other ceiling finish) are adhered.

FIGURE 37.4 Three types of ceiling suspension systems indicating various components.

TABLE 37.1 METAL SUSPENSION SYSTEMS—DUTY CLASSIFICATIONS AND STRUCTURAL CAPACITIES

		Minimum load-carrying capacity (pounds per square foot)		
Duty	**Carrying capacity**	**Direct hung**	**Indirect hung**	**Furring bar**
Light	Supports only the finish material itself	5.0	2.0	4.5
Intermediate	For ordinary ceilings, supports finish material and lightweight components such as light fixtures and ceiling diffusers/grilles	12.0	3.5	6.5
Heavy	Greatest capacity to support finish material and other ceiling-mounted components	16.0	8.0	N/A

SUSPENDED ACOUSTICAL CEILINGS

The most common commercial ceiling consists of modular acoustical panels laid in a direct-hung suspension system known as an *inverted-tee grid*. The acoustical panels are typically 24-in. square, or 24 in. by 48 in., and are laid on the horizontal legs of the inverted tees, lower image in Figure 37.5.

This grid structure is composed of corrosion-resistant steel or extruded aluminum inverted tees (upside-down T-shape). The main runners and cross runners are in the same plane and are assembled by interlocking the pieces to form a unified, modular grid structure, usually on some increment of 12 in. The main runners have slots and holes that have been prepunched in the web at regular spacings to receive the end clips that are on each end of the cross tees.

Acoustical panels and tiles are composed of a variety of materials, including mineral wool, mineral fibers, fiberglass, and/or perlite, which are combined with fillers, binders, and water and then formed into sheets (and cut into panels or tiles) or molded into pans. There are several surface finishes available, including paint, membrane overlay, fabric, and thin metal sheets. Surface textures and patterns include perforations, fissures, embossings, printings, and scorings. Once the grid structure is assembled, Figure 37.6, and the panels and tiles are installed, no other finishing work is necessary.

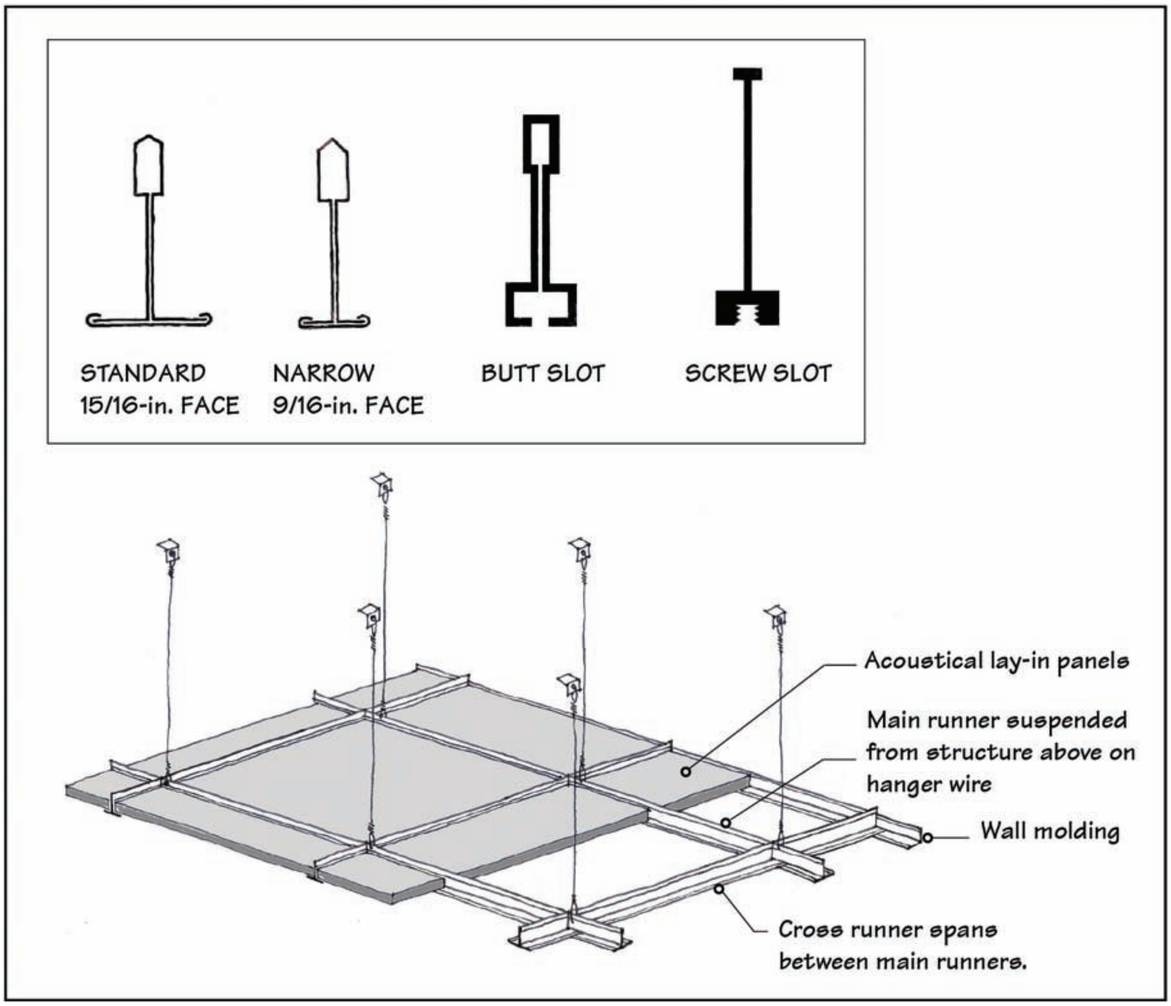

STANDARD
15/16-in. FACE
NARROW
9/16-in. FACE
BUTT SLOT
SCREW SLOT
Acoustical lay-in panels
Main runner suspended from structure above on hanger wire
Wall molding
Cross runner spans between main runners.

FIGURE 37.5 Suspended acoustical ceiling components and typical profiles for inverted tees.

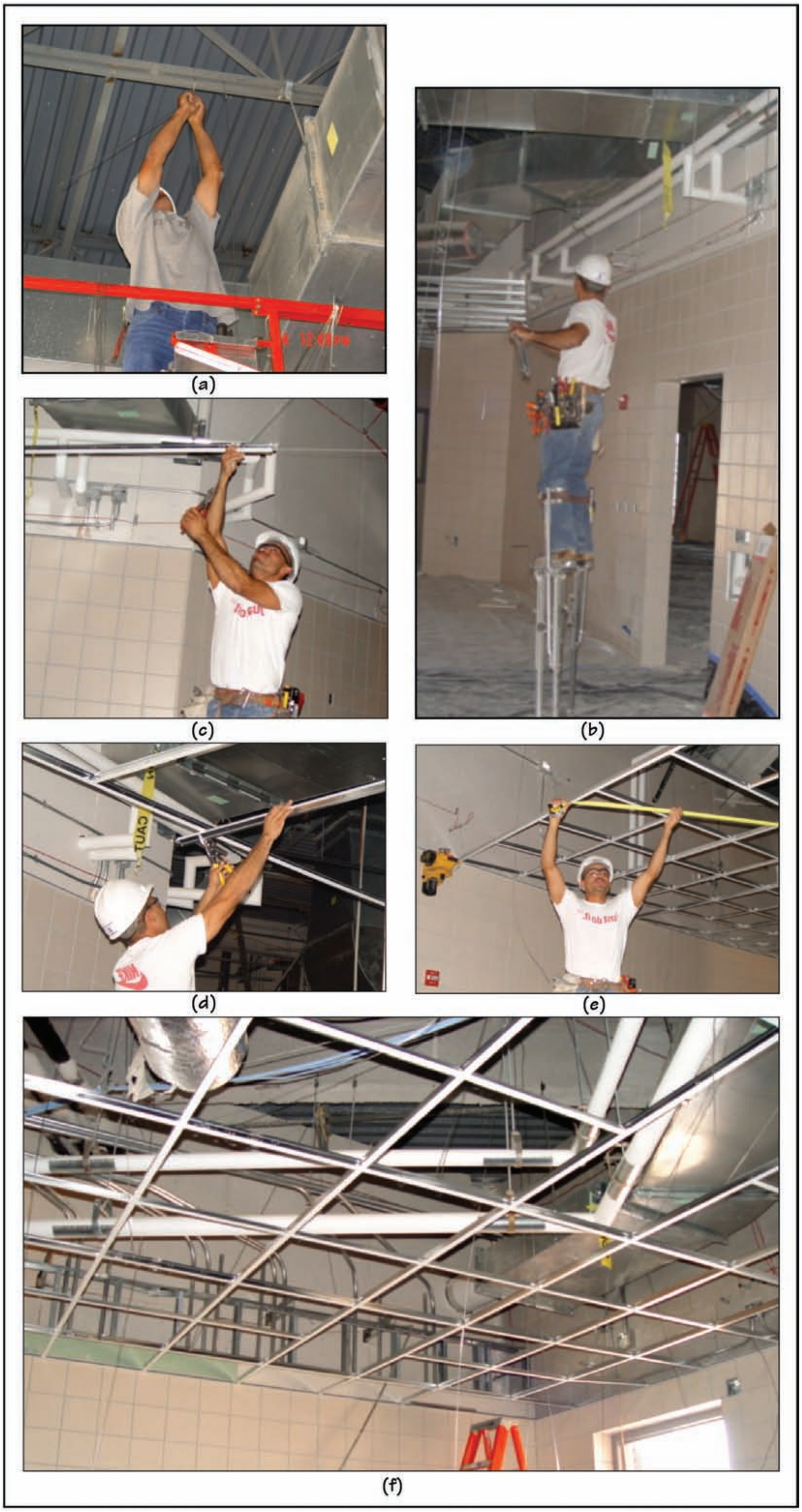


FIGURE 37.6 Installation of a suspended grid. **(a)** Attaching steel hanger wire to the steel structural joist above. In this case, the hanger wire is tied to the steel joist. When a concrete slab or metal deck is present, a hanger wire, with integral clip angel, is usually powder-fastener attached. Hanger wires are always attached to the building structure and not to building utilities. **(b)** Layout begins by establishing the location of the main runners. For most ceilings, installers will use stilts to assist in installation or will use a rolling scaffold. **(c)** Using string and laser level, see (e), installers establish main runner locations. **(d)** Until permanent attachments can be made, installers clamp intersecting tees together. **(e)** Continuing with installation; notice laser level at wall. **(f)** Final suspended grid installation, including openings for light fixtures. (Photos of Vaden's Acoustics & Drywall, Inc. by Gary Yancy of USG Building Systems)

When an acoustical ceiling without an exposed grid is desired, a variation of the inverted-tee grid structure is used. In addition to a suspended grid, metal splines are inserted in the edges of acoustical tiles, usually 12-in. square, which are, in turn, supported on a suspended grid.

SUSPENDED GYPSUM BOARD CEILINGS

The second most common commercial suspended ceiling consists of gypsum board sheets screw attached to an inverted-tee grid structure. The gypsum board is then finished like other gypsum board surfaces. Suspended gypsum board ceilings are versatile because they can be integrated with stud framing hung from the building structure above to form ceilings that have various profiles vertically and horizontally.

The suspended inverted-tee grid structure for gypsum board ceilings is very similar to the grid structure used for suspended acoustical ceilings, except that the bottom surface of the horizontal tee flange is embossed to improve the grip on the gypsum board, Figure 37.7.

SUSPENDED GYPSUM PLASTER CEILINGS AND PORTLAND CEMENT PLASTER SOFFITS

Portland cement and gypsum plasters are heavier than acoustical products and materials and thus require the use of a channel grid structure. Wire lath is attached horizontally to the main and cross runners using steel wire, Figure 37.8; then the plaster is applied.

The channel grid structure is used for ceilings that are heavier than acoustical or gypsum board materials. Using galvanized-steel channel shapes, main runners and cross runners are overlapped, and each intersection is tied with steel wire. Unlike the inverted-tee grid, the spacing of the channels can be adjusted to fit the application conditions, the applied finish, and the component loading.

SUSPENDED SPECIALTY CEILINGS AND SOFFITS

As with so many other building products, a wide variety of specialty ceiling and soffit finishes and materials are available, limited only by the designer's imagination. These systems can be flat planes, squared with corners, curved vertically or horizontally, or formed into the appearance of waves. They can be continuous or broken into sections. Lighting fixtures can be above, within, or below the systems. The following discussion describes just a few suspended specialty ceilings and soffits.

- Canopy ceilings appear as floating ceilings because they emphasize the negative space above and at the sides of suspended ceiling shapes. The materials involved are usually metals, and an almost infinite number of shapes and combinations can be achieved.
- Decorative grids use rectangular main runners and cross runners that are combined and formed into an interlocking grid that is uniform in appearance.

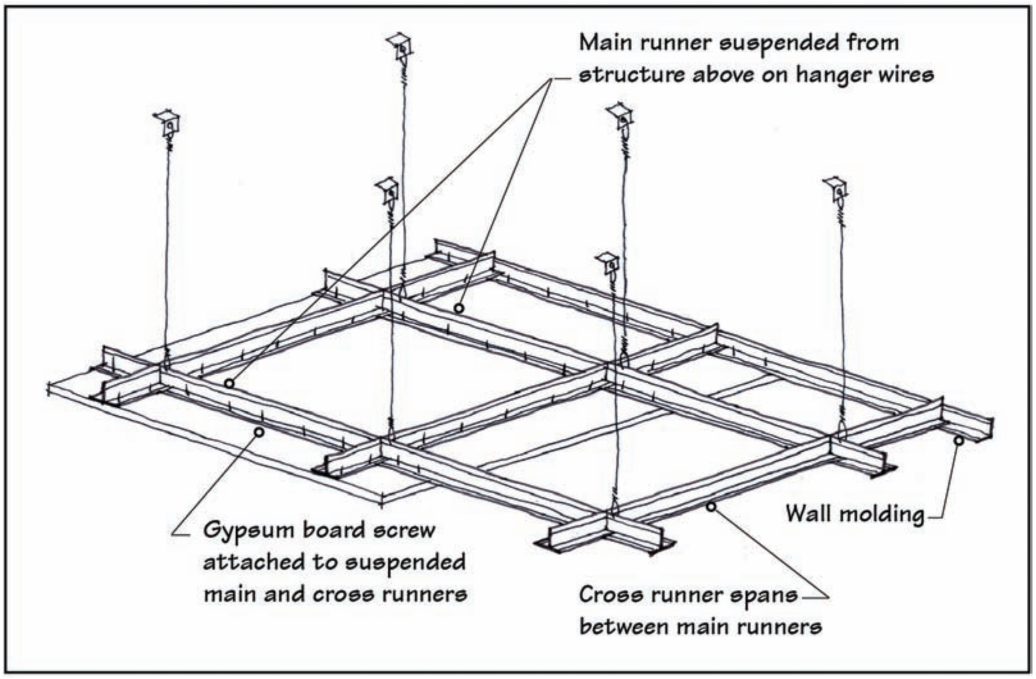

Main runner suspended from structure above on hanger wires
Gypsum board screw attached to suspended main and cross runners
Wall molding
Cross runner spans between main runners

FIGURE 37.7 Suspended gypsum board ceiling components.

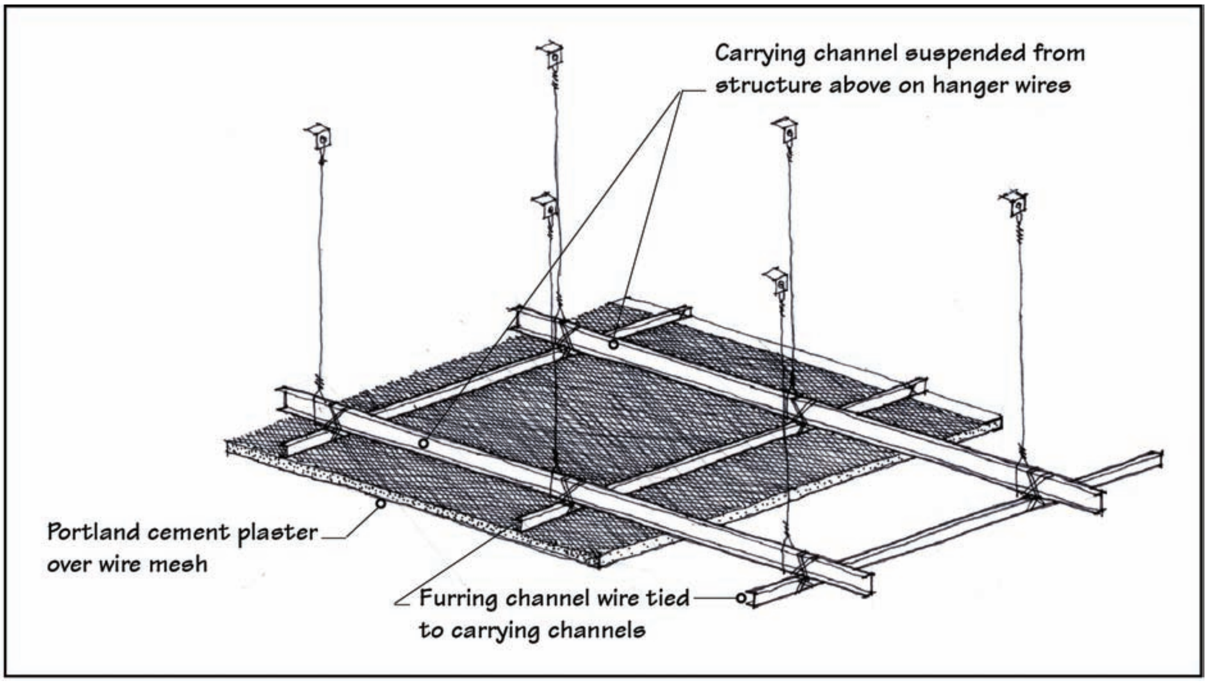

Carrying channel suspended from structure above on hanger wires
Portland cement plaster over wire mesh
Furring channel wire tied to carrying channels

FIGURE 37.8 Suspended Portland cement plaster ceiling/soffit components. Gypsum plaster would be similar, but gypsum board lath would be used in lieu of wire mesh lath.

- Transparent-finished wood panels (very much like wall paneling) can be formed into panels laid into an exposed grid structure or into planks attached to a specialized suspension system.
- Acoustical metal facings, with or without acoustical backings, can be formed into panels or tiles and placed in suspension systems. The surface can be perforated in a variety of patterns, or it can be unperforated.
- Sheet metals can be formed into linear strips that resemble planks, which are attached to a specialized suspension system to achieve a directional look within a space, Figure 37.9. The spaces between the strips can be left open or covered.
- Luminous ceilings combine overhead lighting with either open or translucent (opaque) ceilings to create dramatic effects.

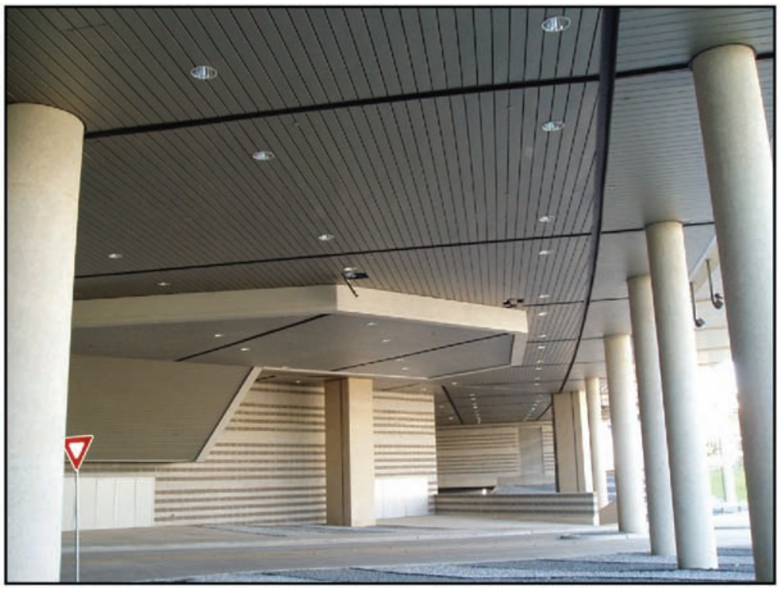


FIGURE 37.9 A suspended linear metal ceiling in an area in which streets and drives pass under a building.

PRACTICE **QUIZ**

Each question has only one correct answer. Select the choice that best answers the question.

6. In a suspended ceiling system, steel hanger wires are supplied by the manufacturer already cut to length.
- **a.** True
- **b.** False

7. The strongest metal suspension system is always a properly installed direct-hung system.
- **a.** True
- **b.** False

8. In suspended acoustical ceilings, the grid structure is made of
- **a.** a hardwood such as oak or maple.
- **b.** extruded aluminum tees.
- **c.** corrosion-resistant steel tees.
- **d.** all of the above.
- **e.** (b) and (c).

9. Acoustical panels and tiles are fabricated using
- **a.** mineral wool, mineral fibers, fiberglass, and/or perlite.
- **b.** fillers, binders, and water.
- **c.** (a) and (b).
- **d.** none of the above.

10. The edges of acoustical panels
- **a.** are designed to rest on the metal suspension system.
- **b.** are available in three different profiles.
- **c.** are snapped into extruded plastic shapes.
- **d.** do not affect the overall pattern of the ceiling.
- **e.** all of the above.

11. Gypsum board is a commonly used finish material. It is typically
- **a.** attached directly to a structural metal or wood light-frame.
- **b.** attached directly to a suspended metal frame.
- **c.** designed to rest on the metal suspension system.
- **d.** all of the above.
- **e.** (a) and (b).

12. The design of a ceiling in a large office building calls for a multilevel series of ceiling planes finished with gypsum board. The most likely method for attaching the ceiling to the structure is to
- **a.** nail gypsum board directly to the wood light-frame structure.
- **b.** screw the gypsum board directly to a suspended metal framework.
- **c.** use lay-in acoustical tile.

13. It is not possible to use lath and plaster with a suspended ceiling structure.
- **a.** True
- **b.** False

14. Ceiling materials are essentially limited to drywall, lath and plaster, and acoustical tiles.
- **a.** True
- **b.** False

REVIEW QUESTIONS

1. Diagram and describe the difference between a ceiling that is attached to the building structure and one that is suspended from the building structure.
2. Examine the ceiling in one of your classrooms. What type of ceiling is it? Do a section sketch illustrating the parts of the system.
3. Use a section sketch and notes to illustrate a direct-hung suspended ceiling.
4. Use a sketch and notes to illustrate two methods of attachment when gypsum board is used as a finish ceiling material.

APPENDIX A

SI System and U.S. System of Units

APPENDIX OUTLINE

RULES OF GRAMMAR IN THE SI SYSTEM

LENGTH, THICKNESS, AREA, AND VOLUME

FLUID CAPACITY

MASS, FORCE, AND WEIGHT

PRESSURE AND STRESS

UNIT WEIGHT OF MATERIALS

TEMPERATURE AND ENERGY

CONVERSION FROM THE U.S. SYSTEM TO THE SI SYSTEM

The system of measurement (or units) commonly used at the present time for the design and construction of buildings in the United States is the foot-pound-second (FPS) system. In this system, length is measured using the foot or its multiples—the yard and the mile—or its submultiple—the inch. Weight is measured in pounds, kilopounds, or ounces. Time is measured in hours, minutes, or seconds. Although the United States was the first country to establish the decimal currency in 1785, it is one of the two (or three) countries where (the nondecimal) FPS system is still used.* Therefore, the FPS system, earlier known as the *Imperial System of Units,* is now commonly known as the *U.S. System of Units* or *U.S. Customary Units*.

The system of units used by the rest of the world is the meter-kilogram-second (MKS) system. A rationalized and more commonly used version of the MKS system is called the *SI system*, popularly known as the *International System of Units*.

The advantage of the SI system (or the MKS system) lies primarily in the fact that the multiples and submultiples of each unit (the secondary units) have a decimal relationship with each other, which makes computations easier and less susceptible to errors. For instance, the secondary units of length, the centimeter and the kilometer, are related to the base unit, the meter, by 10^{-2} and 10^{3}, respectively. By contrast, the length unit in the U.S. system, the foot, does not bear a decimal relationship with its secondary units, the inch, the yard, and the mile.

Twelve prefixes have been standardized in the SI system for use with the base unit to make the secondary units. These prefixes, along with their symbols, are given in Table 1. Note that the prefixes are uppercase for magnitudes 10^{6} and greater and lowercase for magnitudes 10^{3} and lower.

NOTE

The SI system, although commonly referred to as the *International System,* is, in fact, an acronym for *Le Système International d'Unités,* a name given by the thirty-six nations meeting at the eleventh General Conference on Weights and Measures (CGPM) held in Paris in 1960. *(CGPM is an acronym for Conférence Générale des Poids et Mesures.)*

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*Although not yet officially adopted, the SI system is being increasingly used (together with the U.S. System—in a dual-unit format) in several important U.S. publications that regulate building design and construction.

TABLE 1 PREFIXES IN THE IS SYSTEM

Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

The SI system uses seven base quantities—length, mass, time, temperature, electric current, luminous intensity, and amount of substance. The units corresponding to the base quantities and their symbols are listed in Table 2. Of these, only the first four quantities are of interest to design and construction professionals—length, mass, time, and temperature.

Quantities other than the base quantities, such as force, stress, pressure, velocity, acceleration, and energy, and their units are derived from a combination of two or more base quantities. For example, acceleration is the rate of change of velocity, which, in turn, is the rate of change of distance. Consequently, the unit for acceleration is meters per second squared (m/s^2).

Another advantage of the SI system is that there is one and only one unit for each quantity— meter for length, kilogram for mass, second for time, and so on. This is not so in the U.S. system, where multiple units are often used. For instance, power is measured in Btu per hour and also in horsepower.

RULES OF GRAMMAR IN THE SI SYSTEM

The symbols for units in the SI system are always lowercase unless the unit is named after a person, such as Newton, Pascal, Hertz, or Kelvin. In this case, the first letter of the symbol is uppercase and the second letter is lowercase, as in Pa. An exception is, however, made in the case of the liter, which is given the symbol L.

Multiples of base units are given with a single prefix. Double prefixes are not allowed. Thus, megakilometer (Mkm) is incorrect; instead, we use gigameter (Gm). No space is left between a prefix and a symbol. Thus, we use km, not k m.

The product of two or more units in symbolic form is given by using a multiplication dot between individual symbols (e.g., N • m). Mixing symbols and names of units is incorrect (e.g., N • meter).

A space must be left between the numerical value and the unit symbol. Thus, we use 300 m, not 300m. No space, however, is left between the degree symbol and C (Celsius). Plurals are not used in symbols. For instance, we use 1 m and 50 m. Periods are not used after symbols except at the end of a sentence.

In architectural and engineering drawings, dimensions are generally given in millimeters, and when that is done, the use of mm is avoided. For instance, the measurements of a floor tile are given as 300 × 300, not as 300 mm × 300 mm. Larger dimensions may be given in

TABLE 2 BASE QUANTITIES AND THEIR SYMBOLS IN THE SI SYSTEM

Quantity	Unit name	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Temperature	kelvin	K
Electric current	ampere	A
Luminous intensity	candela	cd
Amount of substance	mole	mol

meters, if necessary. For instance, a building may be dimensioned as 30.800 m × 50.600 m in plan (elevation or section), but it is preferable to dimension it as 30,800 × 50,600.

LENGTH, THICKNESS, AREA, AND VOLUME

In the U.S. system, the standard unit of length is the foot: 1 ft = 12 in. Long distances are measured in miles. In the SI system, the standard unit of length is the meter. Most dimensions in the SI system are given in millimeters (mm), where 1 mm = 10^{-3} m. Long distances are given in kilometers (km).

1 ft = 0.3048 m; 1 m = 3.281 ft = 39.37 in.; 1 in. = 25.4 mm
1 mi = 1.609 km

FLUID CAPACITY

Fluid capacity is usually given in gallons in the U.S. system and in liters (L) in the SI system. The imperial gallon is slightly larger than the U.S. gallon, but the imperial gallon is no longer used as a unit.

1 gal (U.S.) = 4 qt = 3.7854 L
1 L = 0.001 m^3 (by definition) = 0.264 gal

MASS, FORCE, AND WEIGHT

In the U.S. system, the unit of weight (and mass) is the pound (lb); the corresponding unit of mass in the SI system is the kilogram (kg).

1 lb = 16 oz = 7,000 gr (grains) = 0.4536 kg
1 kg = 2.205 lb

Force is defined as mass times acceleration. Because the unit of acceleration in the U.S. system is feet/second^2 (ft/s^2), the unit of force is (lb-ft/s^2). This unit is called *pound-force*, usually referred to as the *pound*. In the SI system, the unit of force is $(\text{kg} \cdot \text{m})/\text{s}^2$. This complex unit is called the *newton* (N), after the famous physicist Isaac Newton (1642–1727).

Because the weight of an object is the force exerted on it by the gravitational pull of the earth, the weight is equal to mass × acceleration due to gravity. The acceleration due to gravity on the earth's surface is 9.8 m/s^2. Therefore, the weight of an object whose mass is 1 kg is 9.8 $(\text{kg} \cdot \text{m})\text{s}^2$, or 9.8 N.

We see that in the SI system, there is a clear distinction between the units of mass and the weight of an object. The distinction between the mass and the weight in the U.S. system is rather obscure because the pound is used as the unit for both the mass and the weight of an object.

1 kilogram-force = 9.8 N; 1 lb = 4.448 N; 1 N = 0.2248 lb
1 kilopound (kip) = 1,000 lb = 4.448 kN; 1 kN = 0.2248 kip

NOTE

Some countries that have not fully adonted the SI system use kilogram as the unit for mass as well as force (in the same way as pound is used as a unit for mass and weight). In these countries, the unit for stress is kilogram per square centimeter (kg/cm^2) instead of Pa. Weight density is expressed as kilograms per cubic centimeter (kg/cm^3) instead of N/m^3.

PRESSURE AND STRESS

Because pressure, or stress, is defined as force per unit area, the unit of pressure, or stress, in the U.S. system is lb/ft^2 (psf). Other units commonly used are pounds per square inch (psi) and kilopounds per square inch (ksi). In the SI system, the unit of pressure, or stress, is N/m^2. This unit is called the *pascal* (Pa) after the physicist Blaise Pascal (1623–1662). Thus, 1 N/m^2 = 1 Pa.

1 psf = 47.880 Pa; 1 Pa = 0.208 85 psf
1 psi = 6.895 kPa; 1 kPa = 0.1450 psi

In weather-related topics, the unit of pressure is the atmosphere (atm); 1 atm is the standard atmospheric pressure at sea level.

1 atm = 760 mm of mercury (Hg) = 29.92 in. of Hg = 14.69 psi = 2,115.4 psf = 101.3 kPa. For all practical purposes, the atmospheric pressure may be taken as 2,100 psf or 101 kPa.

UNIT WEIGHT OF MATERIALS

Density is defined as the mass per unit volume. Its units are lb/ft^3 in the U.S. system and kg/m^3 in the SI system, respectively.

$$1\ \text{lb/ft}^3 = 16.018\ \text{kg/m}^3;\quad 1\ \text{kg/m}^3 = 0.064\,243\ \text{lb/ft}^3$$

In building construction, however, we are more interested in the weight density of materials instead of the mass density. Weight density (or simply unit weight) is defined as the weight per unit volume, and its units are lb/ft^3 and N/m^3 in the U.S. system and SI system, respectively.

$$1\ \text{lb/ft}^3 = 157.1\ \text{N/m}^3$$

TEMPERATURE AND ENERGY

In the U.S. system, temperature is measured in degrees Fahrenheit (°F). This scale was introduced during the early eighteenth century. Zero on the Fahrenheit scale was established based on the lowest obtainable temperature at the time, and 100°F was established on the basis of human body temperature as it was then considered to be.

On the Celsius scale (°C), earlier known as the *centigrade scale*, 0°C refers to the freezing point of water and 100°C to the boiling point of water.

The unit of temperature in the SI system is the kelvin (K). The preference for the Kelvin scale over the Celsius scale is due to the fact that on the Kelvin scale, the temperature is always positive. This is not so on the Celsius or the Fahrenheit scale, on which the temperature may be positive or negative. In other words, 0 K (as we know it now) is the lowest obtainable temperature and is, therefore, called *absolute zero*. The relationship between Kelvin and Celsius temperatures is $T°C = (T + 273.15)\ K$. In other words, 20°C = 293.15 K. Other relationships are

$$T°F = [(1.8)T + 32]°C;\quad T°C = [(0.555\ldots)(T - 32)]°F$$

The intervals in both the Kelvin and Celsius scales are equal. Therefore, the Celsius and Kelvin scales start at different points, but their subdivisions are equal. Note that the word *degree* is not used on the Kelvin scale. (That is, we say "8 Kelvins", not "8 degrees Kelvin".) Although Kelvin is the appropriate scale to use in the SI system, degrees Celsius are also used because of the smaller numbers associated with the Celsius scale.

CONVERSION FROM THE U.S. SYSTEM TO THE SI SYSTEM

The conversion of a physical quantity such as length, weight, or stress from the U.S. system to the SI system simply involves using the appropriate conversion factor. A comprehensive list of conversion factors used to convert from the U.S. system to the SI system is given in Table 3. However, when it comes to converting building products' sizes from the U.S. system to the SI system, three types of conversion are possible:

- *Exact Conversion:* This conversion is made simply by multiplying a value given in the U.S. system by the appropriate conversion factor to obtain the corresponding value in the SI system. For example, 12 in. is exactly equal to 304.8 mm.
- *Soft Conversion:* In this conversion, a product's size is not converted, only its description. For example, a manufacturer may decide to continue making 12 in. × 12 in. floor tiles but market them as 305 mm × 305 mm tiles. During the initial period of changeover to the SI system in the building industry, most product sizes will be soft-converted.
- *Hard Conversion:* In hard conversion, the physical size of the product is changed to a new metric equivalent. For example, 12 in. × 12 in. floor tiles will probably be changed to 300 mm × 300 mm tiles. Hard conversion of a product requires a change in the manufacturing equipment and a great deal of coordination among various related products but has the advantage that the product sizes are rationalized.

TABLE 3 UNIT CONVERSION FACTORS

Quantity	To convert from	To	Multiply by
Length	mi	km	1.609 344*
	yd	m	0.9144*
	ft	m	0.304 8*
	ft	mm	304.8*
	in.	mm	25.4*
Area	mi^2	km^2	2.590 00*
	acre	m^2	4 046.87
	acre	ha**	0.404 687
	ft^2	m^2	0.092 903 04*
	in.^{2}	mm^2	645.16*
Volume	yd^3	m^3	0.764 555
	ft^3	m^3	0.028 3168
	100 board feet	m^3	0.235 974
	gal	L	3.785 41
	in.^{3}	cm^3	16.387 064
	in.^{3}	mm^3	16 387.064
Velocity	ft/s	m/s	0.3048
Rate of fluid flow, infiltration	ft^3/s	m^3/s	0.028 3168
	gal/h	mL/s	1.051 50
Acceleration	ft/s^2	m/s^2	0.3048
Mass	lb	kg	0.453 59
Mass per unit area	psf	kg/m^2	4.882 43
Mass density	pcf	kg/m^3	16.018 5
Force	lb	N	4.448 22
Force per unit length	plf	N/m	14.593 9
Pressure, stress	psf	Pa	47.880 26
	psi	kPa	6.894 76
	in. of mercury (in. Hg)	kPa	3.386 38
	in. of Hg (in. Hg)	psf	70.72
	atm***	kPa	101.325
Temperature	°F	°C	5/[9(°F − 32)]
	°F	K	(°F + 459.7)/1.8
Quantity of heat	Btu	J	1055.056
Power	ton (refrigeration)	kW	3.517
	Btu/h	W	0.293 07
	hp	W	745.7
	Btu/(h-ft^2)	W/m^2	3.154 59
Thermal conductivity	Btu-in/(ft^2-h-°F)	W/(m $\cdot$ °C)	0.144 2
Thermal conductance, or thermal transmittance, U	Btu/(ft^2-h-°F)	W/(m^2 $\cdot$ °C)	5.678 263
Thermal resistance	(ft^2-h-°F)/Btu	(m^2 $\cdot$ °C)/W	0.176 110
Thermal capacity	Btu/(ft^2-°F)	kJ/(m^2 $\cdot$ °C)	20.44
Specific heat	Btu/(lb-°F)	J/(kg $\cdot$ °C)	4.186 8
Vapor permeability	perm-in	ng/(Pa $\cdot$ m $\cdot$ s)	1.459 29
Vapor permeance	perm	ng/(Pa $\cdot$ m^2 $\cdot$ s)	57.213 5
Angle	degree	radian	0.017 453

*Denotes exact conversion.
**1 hectare (ha) = 100 m × 100 m.w
***1 atmosphere (atm) = 29.92 in. of mercury.

APPENDIX B

Preliminary Sizing of Structural Members

APPENDIX OUTLINE

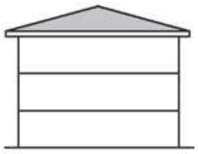
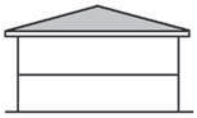
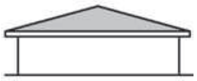
- Conventional Wood Light Frame (WLF) Buildings
- Conventional Cold-Formed Steel Frame (CFSF) Buildings
- Structural Steel Frame Buildings
- Site-Cast Concrete Frame Buildings
- Precast, Prestressed Concrete Members
- Load-Bearing Masonry and Concrete Buildings

The information provided in this appendix is valid only for approximate sizing of structural members during the sketch design (SD) or initial design development (DD) stages of conventional buildings. A structural engineer should be consulted for final member sizes.

CONVENTIONAL WOOD LIGHT FRAME (WLF) BUILDINGS

Wall Framing

Approximate Stud Size and Spacing

Number of stories	Stud size	Stud spacing	
3 stories	2 × 6	16 in. o.c.	
2 stories	2 × 6	16 in. o.c.	
	2 × 4	12 in. o.c.	
1 story	2 × 4	24 in. o.c.	

1. Stud size and spacing are for approximately 10-ft-high studs. For tall walls, such as those used in double-height spaces, doubled studs and (or) closer stud spacing may be required.
2. In cold climates, the stud size may be governed by insulation requirements. For example, 2 × 6 studs may be necessary where 2 × 4 studs are structurally adequate.
3. In high-wind regions, the exterior walls may require larger studs and (or) closer spacing or doubled studs.

FLOOR FRAMING

Lumber Joists—Approximate Span Capabilities

	Joist spacing		
Joist size	**12 in. o.c.**	**16 in. o.c.**	**24 in. o.c.**
2 × 6	11 ft	10 ft	9 ft
2 × 8	15 ft	13 ft	11 ft
2 × 10	19 ft	17 ft	14 ft
2 × 12	23 ft	20 ft	16 ft

I-Joists—Approximate Span Capabilities

	i-joist spacing		
I-joist depth	**12 in. o.c.**	**16 in. o.c.**	**24 in. o.c.**
$9\frac{1}{2}$ in.	18 ft	16 ft	14 ft
$11\frac{7}{8}$ in.	21 ft	19 ft	15 ft
14 in.	24 ft	20 ft	17 ft
16 in.	28 ft	24 ft	19 ft

Trussed Joists—Span Capabilities

Unlike lumber or I-joists, trussed joists are custom manufactured for a project and are not trimmable. Typical spacing of trussed joists = 24 in. o.c.

$$\textbf{Approx. joist depth} = \frac{\textbf{joist span}}{\textbf{18}}$$

Example

If joist span = 30 ft, approximate joist depth = (30 × 12)/18 = 20 in.
Because trussed joists are made of 2 × 4 lumber, the width of joists is $3\frac{1}{2}$ in.

ROOF FRAMING

Sawn Lumber Rafters—Approximate Span Capabilities

	Rafter spacing		
Rafter size	**12 in. o.c.**	**16 in. o.c.**	**24 in. o.c.**
2 × 6	14 ft	13 ft	12 ft
2 × 8	19 ft	18 ft	15 ft
2 × 10	25 ft	22 ft	18 ft

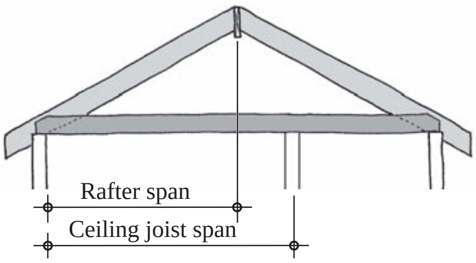
The above table applies to a roof live load (or snow load) ≤20 psf and a light roof cover (such as asphalt shingles). If the snow load exceeds 20 psf and (or) the roof cover is heavier (such as clay or concrete tiles), the span capability of a given rafter size will be smaller.

Sawn Lumber Ceiling Joists—Approximate Span Capabilities

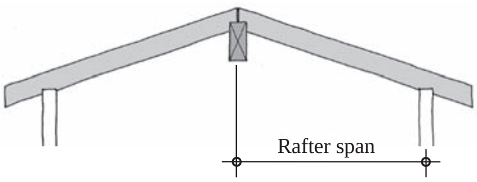
	Joist spacing		
Joist size	**12 in. o.c.**	**16 in. o.c.**	**24 in. o.c.**
2 × 6	18 ft	16 ft	14 ft
2 × 8	24 ft	22 ft	18 ft
2 × 10	—	—	22 ft

The above table applies to an uninhabitable attic without storage.

A dash (—) indicates that the span capability exceeds 26 ft—the maximum sawn lumber length available.



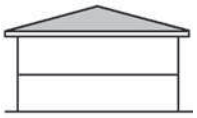
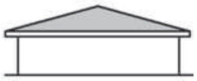
Because the span of a hip or valley rafter is larger than the common rafters, hip or valley rafters are generally one size larger than the common rafters. Thus, for 2 x 8 common rafters, a hip or valley rafter is generally 2 x 10.



CONVENTIONAL COLD-FORMED STEEL FRAME (CFSF) BUILDINGS

WALL FRAMING

Approximate Stud Size and Spacing

Number of stories	stud size	stud spacing	
2 stories	550S162–33 350S162–43	24 in. o.c. 16 in. o.c.	
1 story	350S162–33	24 in. o.c.	

Stud size and spacing are based on sheet steel with a yield strength of 33 ksi. The other commonly used yield strength is 50 ksi (see Chapter 17).

550S162–33 implies a stud (joist or rafter) with a web depth of 5.5 in. and a flange width of 1.625 in., made of 33-mil (0.033-in.)-thick sheet steel (see Chapter 17).

1. Stud size and spacing are for approximately 10-ft-high studs. For tall walls, such as those used in double-height spaces, larger stud size and (or) thicker sheet steel or closer spacing of studs may be required.

2. In cold climates, the stud size may be governed by insulation requirements. For example, 550S162 studs may be necessary where 350S162 studs are structurally adequate.
3. In high-wind regions, the exterior walls may require larger studs, studs made of thicker sheets, or higher yield strength.

FLOOR FRAMING

Joists—Approximate Span Capabilities

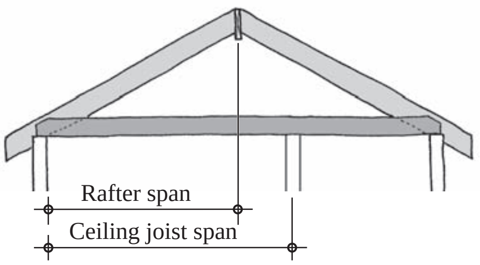
	Joist spacing	
Joist size	**16 in. o.c.**	**24 in. o.c.**
550S162–54	11 ft	10 ft
800S162–54	15 ft	13 ft
1000S162–54	18 ft	17 ft
1200S162–54	21 ft	18 ft

1. For a given joist size, the span capability can be increased by increasing the sheet thickness. Commonly used sheet thicknesses for joists are 33, 43, 54, 68, and 97 mil.
2. The span capabilities given here are for the intermediate sheet thickness of 54 mil.

ROOF FRAMING

Rafters—Approximate Span Capabilities

	Rafter spacing	
Rafter size	**16 in. o.c.**	**24 in. o.c.**
550S162–54	18 ft	15 ft
800S162–54	24 ft	20 ft
1000S162–54	28 ft	23 ft
1200S162–54	30 ft	25 ft



1. The above table applies to a roof live load (or snow load) ≤20 psf and a light roof cover (such as asphalt shingles). If the snow load exceeds 20 psf and (or) the roof cover is heavier (such as clay or concrete tiles), the span capability of a given rafter size will be smaller.
2. For a given rafter size, the span capability can be increased by increasing the sheet thickness. Commonly used sheet thicknesses for rafters are 33, 43, 54, 68, and 97 mil.
3. The span capabilities given here are for the intermediate sheet thickness of 54 mil.

Ceiling Joists—Approximate Span Capabilities

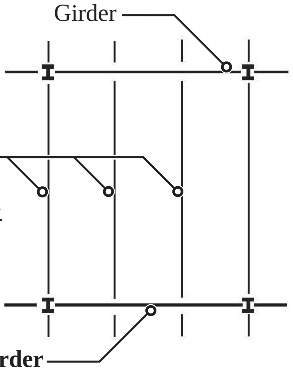
	Joist spacing	
Joist size	**16 in. o.c.**	**24 in. o.c.**
550S162–54	18 ft	15 ft
800S162–54	20 ft	18 ft
1000S162–54	21 ft	19 ft
1200S162–54	23 ft	20 ft

1. The above table applies to an uninhabitable attic without storage.
2. For a given joist size, the span capability can be increased by increasing the sheet thickness. Commonly used sheet thicknesses for rafters are 33, 43, 54, 68, and 97 mil.
3. The span capabilities given here are for the intermediate sheet thickness of 54 mil.

STRUCTURAL STEEL FRAME BUILDINGS

FLOORS AND ROOFS

W-section Girders and Beams



Approx. depth = $\frac{\text{Span}}{22}$

Typical spacing of beams = 8 to 12 ft

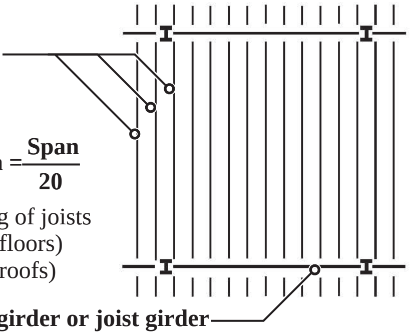
Approx. depth = $\frac{\text{Span}}{16}$

but not less than beam's depth

Nominal Depths of W-Sections in inches

44, 40, 36
33, 30, 27, 24, 21
18, 16, 14, 12, 10, 8, 6, 4

Girders and K-series joists



Approx. depth = $\frac{\text{Span}}{20}$

Typical spacing of joists
= 2 to 4 ft (for floors)
= 4 to 6 ft (for roofs)

Approx. depth = $\frac{\text{Span}}{16}$ (for W-section girder)

Approx. depth = $\frac{\text{Span}}{14}$ (for joist girder)

Standard Depths of K-Series Joists in inches

8, 10, 12, 14, 16, ...30

Example 1

Determine the approximate depths of the beams and girders for the floor of Figure 19.5.

Solution

The maximum span of the girder is 26.5 ft. Therefore, approximate girder depth = (26.5 × 12)/16 = 19.9 in., or 20 in. The nearest W-section is W21. Hence, use a W21 girder.

The maximum beam span is 30 ft. Therefore, approximate beam depth = (30 × 12)/22 = 16.4 in. Hence, use a W16 beam.

COLUMNS

Interior Columns

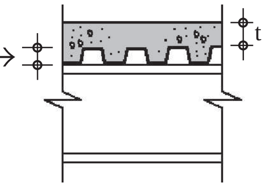
To approximate the size of an interior column, compute the total floor area supported by the column on all floors and then select the column size from the following table.

Column size		Maximum floor area on all floors
I	8 in. x 8 in.	2,000 sq. ft
I	10 in. x 10 in.	3,000 sq. ft
I	12 in. x 12 in.	4,500 sq. ft
I	14 in. x 14 in.	6,000 sq. ft

Composite Floor Decks

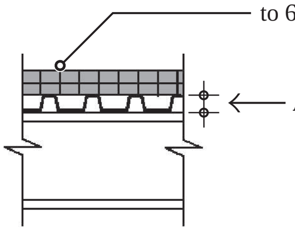
Approx. deck depth = 2 in.

Approximate thickness of concrete (t) above deck
4 in. for 2-h fire-rated floor
3 in. for 1-h fire-rated floor



Roof Decks

Thickness of rigid insulation = 3 in. to 6 in. depending on the climate



Approx. deck depth = 1-1/2 in.

Exterior Columns

Although the floor area supported by an exterior column is less than that of an interior column, exterior columns will generally support (exterior) walls, which generally are not supported by interior columns. Therefore, exterior columns may be assumed to be the same size as interior columns.

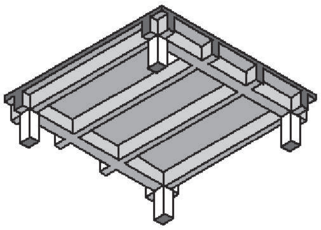
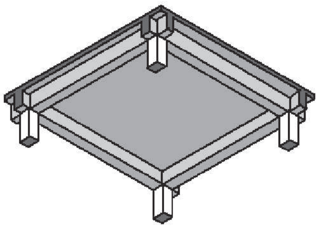
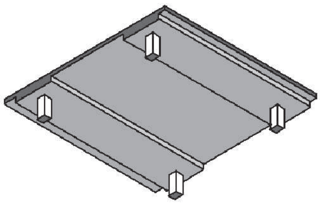
Example 2

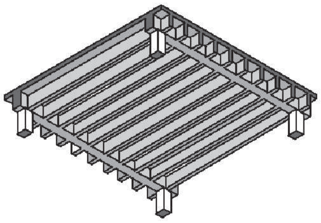
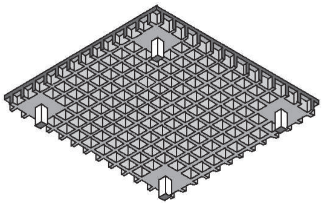
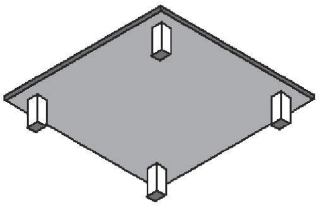
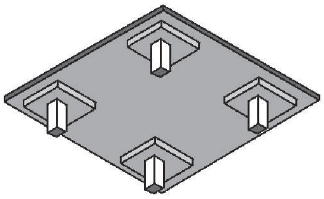
If the building in Figure 19.5 is five stories tall, determine the approximate size of the columns.

Solution

We will base the column size on the maximum floor area supported by an interior column. The largest bay size is $(30.0 \times 26.5) = 795\ \text{ft}^2$. The total area on all five floors is $5(795) = 3{,}975\ \text{ft}^2$. From the table above, an approximate column size is a W12 column (web depth approximately 12 in.).

SITE-CAST CONCRETE FRAME BUILDINGS

 **Beam and Girder-Supported One-Way Solid Slab**	*Reinforced Concrete Girder* **Approx. depth** $= \dfrac{\textbf{span}}{\textbf{12}}$ Width = 0.6 (depth) *Beam* **Approx. depth** $= \dfrac{\textbf{span}}{\textbf{15}}$ Width = 0.6 (depth) *Slab* **Approx. thickness** $= \dfrac{\textbf{span}}{\textbf{24}}$ Typical distance between beams = 8 ft to 15 ft	*Posttensioned Concrete Girder* **Approx. depth** $= \dfrac{\textbf{span}}{\textbf{18}}$ Width = 0.6 (depth) *Beam* **Approx. depth** $= \dfrac{\textbf{span}}{\textbf{20}}$ Width = 0.6 (depth) *Slab* **Approx. thickness** $= \dfrac{\textbf{span}}{\textbf{40}}$ Typical distance between beams = 15 ft to 25 ft	Span for girder is clear distance between columns, and span for beams is clear distance between girders. Depth of girder or beam includes thickness of slab. Span for slab is clear distance between beams. As far as possible, girder and beam depths should be the same. Therefore, the girder should span along the shorter direction. Round beam and girder widths and depths to whole inches. Round slab thickness to $\frac{1}{2}$ inch, not less than 4 in. Slab thickness may be governed by fire-resistance requirements.
 **Two-way Solid Slab**	*Reinforced Concrete* *Beam* **Approx. depth** $= \dfrac{\textbf{span}}{\textbf{15}}$ Width = 0.6 (depth) *Slab* **Approx. thickness** $= \dfrac{\textbf{span}}{\textbf{36}}$ Typical column spacing = 20 ft to 25 ft	*Posttensioned Concrete* *Beam* **Approx. depth** $= \dfrac{\textbf{span}}{\textbf{20}}$ Width = 0.6 (depth) *Slab* **Approx. thickness** $= \dfrac{\textbf{span}}{\textbf{42}}$ Typical column spacing = 25 ft to 30 ft	Span for beams is clear distance between columns. Span for slab is the longer of the two clear distances between beams. Round beam width and depth to whole inches. Round slab thickness to $\frac{1}{2}$ inch, not less than 4 in. Slab thickness may be governed by fire-resistance requirements. As far as possible, distance between columns in both directions should be the same.
 **One-Way Band Beam Slab**	*Reinforced Concrete Beam* **Approx. depth = 2.0 to 2.5 (slab thickness)** Width = 0.25 to 0.3 (center-to-center beam spacing) *Slab* **Approx. thickness** $= \dfrac{\textbf{span}}{\textbf{24}}$ Typical column spacing = 25 ft to 30 ft	*Posttensioned Concrete Beam* **Approx. depth = 2.0 to 2.5 (slab thickness)** Width = 0.25 to 0.3 (center-to-center beam spacing) *Slab* **Approx. thickness** $= \dfrac{\textbf{span}}{\textbf{40}}$ Typical column spacing = 30 ft to 40 ft	Span for slab is clear distance between beams. Round beam width and depth to whole inches. Round slab thickness to $\frac{1}{2}$ inch. Slab thickness should not be less than 4 in. Slab thickness may be governed by fire-resistance requirements.

 **One-Way Joist Slab**	*Reinforced Concrete* *Beam* **Depth** = **same as joists** Width = 1.75 (joist depth) Joist **Approx. depth** = $\frac{\textbf{span}}{\textbf{18}}$ Width = 5 in. (standard-module pans), 7 in. for wide-module pans *Slab* **Thickness** = **3 in.** (standard-module pans), **4 in.** (wide-module pans) Typical column spacing = 25 ft to 40 ft	*Post-tensioned Concrete* *Beam* **Depth same as joists** = Width = 1.25 (joist depth) Joist (Reinforced Concrete) **Approx. depth** = $\frac{\textbf{span}}{\textbf{18}}$ Width = 5 in. (standard-module pans), 7 in. for wide-module pans *Slab* **Thickness 3 in.** (standard-module pans), **4 in.** (wide-module pans) Typical column spacing = 35 ft to 50 ft	Span for joists is clear distance between beams. Depth of joists or beams includes slab thickness. Round joist depth to pan depth + slab thickness. Slab thickness may be governed by fire-resistance requirements.
 **Two-Way Joist (Waffle) Slab**	*Reinforced Concrete* *joist* **Approx. depth** = $\frac{\textbf{span}}{\textbf{22}}$ **Width = 5in. to 6 in.,** depending on dome size *Slab* **Thickness = 3in. to 4 in.** Typical column spacing = 30 ft to 45 ft	*Posttensioned Concrete* *joist* **Approx. depth** = $\frac{\textbf{span}}{\textbf{30}}$ **Width = 5in. to 6 in.,** depending on dome size *Slab* **Thickness = 3 in. to 4 in.** Typical column spacing = 40 ft to 60 ft	Depth of joists includes slab thickness. Round joist depth to dome depth + slab thickness. Slab thickness may be governed by fire-resistance requirements. The number of domes filled around columns is a function of column spacing, floor load, and dome size. Beams may be used in place of filled domes.
 **Flat Plate**	*Reinforced Concrete* *Slab* **Approx. thickness** = $\frac{\textbf{span}}{\textbf{30}}$ Typical column spacing = 15 ft to 20 ft	*Posttensioned Concrete* *Slab* **Approx. thickness** = $\frac{\textbf{span}}{\textbf{36}}$ Typical column spacing = 25 ft to 30 ft	Slab span is (longer) clear distance between columns. As far as possible, distance between columns in both directions should be the same. Slab thickness may be governed by fire-resistance requirements.
 **Flat Slab**	*Reinforced Concrete* *Slab* **Approx. thickness** = $\frac{\textbf{span}}{\textbf{35}}$ Typical column spacing = 20 ft to 30 ft	*Posttensioned Concrete* *Slab* **Approx. thickness** = $\frac{\textbf{span}}{\textbf{45}}$ Typical column spacing = 30 ft to 45 ft	Slab span is (longer) clear distance between columns. As far as possible, distance between columns in both directions should be the same. Slab thickness may be governed by fire-resistance requirements.

Columns

Column size depends on various factors, such as the total floor area supported by the column, concrete strength, amount of reinforcement, column height, and whether the column is part of the lateral load resistance system of the building. For conventional buildings in which the lateral load is resisted by shear walls, the following rule of thumb may be used for the approximate size of an interior column:

$$\text{Area of column} = \frac{\text{total floor area supported by column}}{\text{10 to 20(depending on concrete strength}}\text{not less than 10 in. in any direction}$$

As far as possible, column size should be the same for interior and exterior columns and from floor to floor. Note that the amount of reinforcement and the concrete strength in a column can be increased toward the lower floors.

Example: Determine the column size required for a square reinforced-concrete column at the ground floor of a building supporting 1,000 ft^2 at each floor. Number of floors = 4.

Solution:

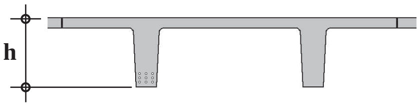
$$\text{Area of column} = \frac{4{,}000}{10} = 400\ \text{in.}^2$$

Hence, approx. column size = 20 in. × 20 in.

PRECAST, PRESTRESSED CONCRETE MEMBERS

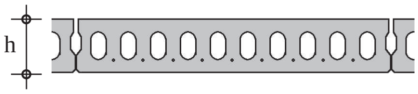
Double-T Units

Approx. depth, $h = \frac{\text{Span}}{28}$



Hollow-core slabs

Approx. depth, $h = \frac{\text{Span}}{40}$



LOAD-BEARING MASONRY AND CONCRETE BUILDINGS

Reinforced-Concrete Masonry Bearing Walls in Residential (e.g., Apartment and Hotel) Buildings

8-in.-thick, CMU walls for up to 8-floor-high buildings.

10-in.-thick CMU walls for 11- to 15-floor-high buildings.

12-in.-thick CMU walls for 16- to 20-floor-high buildings.

Upper floors in 10-in.- or 12-in.-thick wall structures may be constructed of 8-in.-thick walls.

Reinforced-Concrete Masonry Bearing Walls in Single-Story, Long-Span Structures (e.g., Gymnasiums)

10-in.- or 12-in.-thick CMU walls, depending on the span.

Site-Cast Reinforced-Concrete Bearing Walls in Residential Buildings

6-in.-thick site-cast reinforced-concrete walls for up to 20-floor-high buildings.

Precast-Concrete Tilt-Up Walls

The thickness of tilt-up walls in a single-story building can be approximated by dividing the wall height by 48 (not less than 6 in.). For two- or three-story buildings, slightly thicker walls may be needed.

GLOSSARY

A

Abrasive blasting A method of roughening a concrete or steel surface by an abrasive medium, such as sand, under high air pressure.
Acid etching A method used to expose the aggregate on a concrete surface through the use of a dilute acid wash.
Acoustical materials See *sound-absorbing materials*.
ACQ See *alkaline copper quat*.
ADA Americans with Disabilities Act.
Adhered veneer A thin finish material, such as thin brick or tile, that is adhered directly to a backup wall with mortar or adhesive.
Adobe Sun-dried clay masonry units, generally molded on site.
Aggregate Granular materials, including gravel, sand, crushed stone, expanded shale, and slag, that serve as filler in a concrete mix.
Air retarder A microperforated plastic sheet that prevents the passage of outside air through a wall or roof assembly but allows water vapor to pass through.
Air seasoning A method of drying lumber in which lumber members are stacked to allow free circulation of air around them.
Alkaline copper quat (ACQ) A chemical used for wood preservation.
Alloy A chemical combination of two or more metals.
Anchored veneer A cladding system (usually exterior) in which masonry units are mechanically anchored to the backup wall.
Anisotropic material A material that has different properties in different directions (e.g., wood). See also *isotropic material*.
Annealed glass Flat glass obtained by heating and then gradually cooling it to relieve internal stresses that develop during the early stage of its manufacturing process. Annealed glass is the basic form of flat glass.
Arch A curved structural member that spans over a wall opening and carries loads in compression.
Arching action A structural action in which a vertical load on a wall or beam translates into two inclined loads; generally occurs in a deep beam or wall.
Architectural concrete Concrete that is obtained from a specially designed formwork to give a smooth, patterned, textured, or otherwise detailed surface finish on concrete.
Architectural precast concrete Nonstructural precast concrete, as in a concrete curtain wall.
Architectural sheet-metal roof A roof covering made of sheet metal (e.g., standing seam roof, batten seam roof), applied over a structural roof deck and underlayment.
Ashlar Stone dressed with square-cut edges and laid in a coursed or random pattern in a wall.
Asphalt A tacky black liquid derivative of the petroleum-distillation process, used in roofing and waterproofing applications.
Asphalt-saturated felt An organic paper felt that is saturated with asphalt, typically used as an underlayment in steep roofs (sometimes in walls).
Asphalt shingles A roofing unit composed of heavy organic paper or fiberglass felt saturated (or treated and coated) with asphalt and faced with mineral granules.
Asphalt-treated felt A fiberglass felt that is treated with asphalt, typically used in built-up roofs.
ASTM American Society for Testing and Materials.
Attactic polypropylene (APP) A polymer used to obtain an APP modified-bitumen roof membrane.
Auger A tool for drilling holes in wood or soil. Large mechanized augers drill holes in the ground for piers, piles, or caissons.
Axial A direction that is parallel to the length of a structural member. For a column, the axial direction is vertical; for a horizontal beam, the axial direction is horizontal.

B

Backer rod A compressible spherical foam rod used to control the depth of an elastomeric sealant, which allows the tooling of the sealant.
Backfill Soil used to fill the space between the foundation and the boundaries of an excavation. Generally, the soil excavated from foundation trenches and pits is used as backfill unless it is unsuitable.
Backup wall Load-bearing or non-load-bearing wall to which exterior cladding is adhered or anchored.
Balance point temperature Exterior temperature at which heat loss through the building envelope equals heat gain from interior activities such as cooking, lighting, and human occupancy.
Ballast (in roofing) Aggregate or concrete pavers used over a loose-laid, single-ply roof membrane to resist wind uplift and protect the membrane from degradation by solar radiation.
Balloon frame One of the two wood light frame construction systems in which the studs extend from the foundation to the roof, bypassing the intermediate floor(s). See also *platform frame*.
Ballooning Interior pressurization of a building due to high wind. It typically occurs in buildings that have large openings on only one exterior face, such as an aircraft hangar.
Baluster Vertical support of a staircase handrail.
Barrier wall An exterior wall that resists water leakage by providing an impervious barrier or by serving as a water reservoir.
Basement Below-ground portion of a building.
Basic wind speed Peak 3-s gust wind speed with a 50-year recurrence interval, used to determine wind loads on a building.
Batt Precut units of fiberglass insulation sized to fit between wall studs, ceiling joists, or rafters.
Batten A long, narrow strip of wood.
Batten bar A long metal or plastic bar used in a mechanically fastened single-ply roof membrane.
Bay In a building structure, regular, repeated space defined by four adjacent columns and beams (and/or girders) that span between them.
Beamless floor A reinforced-concrete slab supported directly on columns (without supporting beams).

Bearing pad A block of high-strength plastic, metal, or rubber placed under a beam or curtain wall to distribute the load on a larger area of the supporting member.

Bearing plate A steel plate welded to the base of a steel column to distribute the column load on a larger area of the footing. Also a steel plate welded to the ends of a steel joist or beam.

Bearing wall A wall that carries gravity loads from the floor(s) and/or roof.

Bed joint Horizontal mortar joint in a masonry wall. See also *head joint*.

Bending Deformation of a structural member caused by a force acting perpendicular to the member axis.

Bent glass Flat glass bent to shape by heating.

Bentonite clay A highly expansive clay typically used as slurry to fill the excavation for a concrete wall.

Billet A large rectangular bar of cast steel used to roll finished shapes, such as smaller bars and rods.

Bioclimatic glass curtain wall See *double-skin glass curtain wall*.

Bitumen A waterproofing compound (asphalt or coal tar) used for roofing and waterproofing.

Blast furnace A furnace used to melt iron ore.

Blocking Short pieces of lumber that fit between adjacent wood joists, rafters, or studs to provide lateral stability and additional nailing members.

Bloom Steel cast in a large rectangular section, which is then used to make wide-flange sections, angles, and channels by the hot-rolling process.

Board foot The amount of lumber contained in a 1-in.-thick board that measures 1 ft by 1 ft.

Board lumber Lumber that is less than 2 in. (nominal) thick.

Bolt A threaded steel rod with a fixed head at one end and closed with a nut at the other end.

Bond beam A continuous reinforced beam embedded in a masonry wall (generally at the floor and roof levels) formed either by bond beam masonry units or site-cast concrete.

Bond breaker A material used to prevent the adhesion of an elastomeric sealant to a backup surface.

Bond pattern The pattern used to arrange masonry units in a wall.

Breathable material A material that allows water vapor to pass through but is resistant to the passage of (bulk) water. An air retarder (sheet or liquid-applied film) is required to be breathable.

Brick A small masonry unit, generally manufactured from clay. Concrete bricks are also available.

Brick ledge Depressed portion of a concrete foundation to support the first story of brick veneer.

Bridging Structural members, laid perpendicular to wood or steel framing members, to stabilize them against overturning and brace them against buckling.

Brittle material A material that deforms little before failure. It is generally stronger in compression than in tension.

Brown coat The second layer of base coat in portland cement plaster (stucco) applied on metal lath.

Buckling A type of failure that results in the sudden bending of a slender structural member subjected to excessive axial loading.

Building brick A type of clay brick recommended for interior applications, with less-stringent durability specifications than facing brick.

Building code A legal document that regulates the design and construction of buildings to ensure that the buildings meet minimum standards of health, safety, and welfare.

Building component A part of a building that performs a specific function, that is, a window, door, or wall assembly.

Building envelope All building components that separate the building's interior from the exterior environment.

Building expansion joint See *building separation joint*.

Building information modeling (BIM) A three-dimensional software tool for designing buildings in real time, which facilitates design and construction and also allows the extraction of conventional two-dimensional plans, elevations, and sections. The model contains information about the attributes of building materials and assemblies, and therefore can be used after construction for repairs, alterations, and maintenance over the building's entire life.

Building movement joint See *building separation joint*.

Building separation joint A continuous joint that extends through all floors and the roof of a building, dividing the building into smaller buildings that can move independently of each other, generally $1\frac{1}{2}$ to 2 in. wide.

Built-up beam A beam made by combining two or more standard structural members.

Built-up roof (BUR) membrane A multi-ply roof membrane composed of alternating layers of felt and moppings of bitumen with a top cover of aggregate.

C

Caisson A large-diameter, deep reinforced-concrete foundation element made by drilling a hole into the ground and filling it with concrete; an enclosure that permits excavation work to be carried out underwater.

Calcium silicate masonry unit Sand-lime bricks or blocks cured in an autoclave to enhance the pozzolanic reaction between sand and lime.

Camber An upward curvature introduced in a beam to ensure that it will be flat under dead loads.

Cant strip A triangular strip of perlite board or pressure-treated wood to provide a smooth transition between a horizontal and a vertical surface on a roof, required with a built-up or modified-bitumen roof membrane.

Capital Upper part of a column, generally of a larger cross section than the column.

Carriage An inclined structural member (beam) that supports a stair.

Cast-in-place (CIP) concrete See *site-cast concrete*.

Cast iron An iron-carbon alloy formed by casting molten iron in a sand mold and milling to the final shape—relatively brittle and nonmalleable.

Caulk Soft, pliable material (such as polyisobutyline and acrylic) used to fill narrow, nonmovement joints between building components.

Ceiling The visible overhead interior surface of a room.

Cells Voids in concrete masonry units; voids in foamed insulation; microscopic voids in wood.

Centering Temporary formwork for constructing an arch, vault, or dome.

Ceramic material A material produced by firing clay in a high-temperature kiln, such as brick, tile, or porcelain.

Certified wood Wood obtained from sustainable forestry practices.

Chair A small support to raise steel reinforcing bars above the surface of the formwork or ground.

Charcoal The heating of wood in the absence of oxygen drives water and other volatile compounds (a process called pyrolysis) leaving a dry, porous, soft black substance referred to as charcoal because it resembles coal.

Chimney A hollow vertical structure lined with an internal flue to carry smoke and other effluents from wood or charcoal fires used for heating a building.

Chord Member of a truss; can be the top or bottom chord of a truss.

CIP concrete See *cast-in-place concrete*.

Cladding Exterior weather-resistant layer of a wall assembly.

Clad window Framing members of a wood window clad in aluminum, polyvinyl chloride, or fiberglass on the outside to increase wood's durability.

Clapboard A type of horizontal lap siding

CMU See *concrete masonry unit*.

Coal tar A tacky black liquid derivative of the coal-distillation process, used in roofing and waterproofing applications.

Coefficient of friction A measure of the resistance to sliding between the contact surfaces of two components.

Cohesive soil A soil, such as clay, whose particles tend to adhere (cohere) to each other in the presence of water.

Cold-formed metal framing See *light-gauge steel framing*.

Cold joint See *construction joint*.

Column An upright vertical structural member that supports a slab, beam, or truss.

Column cover Preformed exterior cladding element that covers a column for aesthetic purposes.

Column splice A method of connecting the lower part of a tall steel column with the upper part. Column splices are typically provided every two stories.

Combustible A material that will ignite in the presence of an open flame or high temperature.

Commissioning A process of adjusting the performance of individual components of the mechanical and electrical systems of a building to achieve energy efficiency.

Compaction A decrease in the amount of void space in a soil mass brought about by mechanical action (e.g., tamping) or a natural process, resulting in a densified soil mass.

Composite deck Corrugated-steel floor deck, which acts as formwork and primary reinforcement for a concrete slab.

Compression Stress created in a structural member as a result of bending or axial compressive force.

Compressive strength Measure of the ability of a material to resist compressive force.

Concave joint A type of mortar joint profile that is most weather resistant.

Concrete A composite material consisting of portland cement, coarse aggregate (crushed stone), fine aggregate (sand), and water.

Concrete admixture Material added to a concrete mix to influence its performance.

Concrete block See *concrete masonry unit*.

Concrete masonry unit Standardized masonry unit made of concrete and consisting of face shells and webs surrounding two or three voids, called cells.

Condensation resistance factor A measure of the potential for condensation to occur on a glazed assembly (window or glass curtain wall).

Conduction A mode of heat transfer in a solid.

Conduit A hollow metal or plastic tube used as protective cover for electric wires.

Construction documents Documents used by a contractor to construct a building, including drawings and specifications.

Construction drawings Drawings used by a contractor to construct a building.

Construction joint A nonmovement joint resulting when fresh concrete is placed against previously placed concrete.

Construction manager A manager hired by the owner to coordinate and supervise the work of multiple contractors. A project with a construction manager does not generally have a general contractor.

Control joint A sawed or tooled joint on the top surface of a concrete slab-on-ground; a continuous vertical joint in a concrete masonry wall.

Convection A mode of heat transfer in liquids and gases.

Conveying equipment Mechanical equipment that is used to move people or products vertically and/or horizontally through a building.

Coping A protective cap or cover used on the exposed top of a wall, typically sloped to shed water.

Core holes Holes in an extruded brick to provide uniform drying and firing.

Corrosion An electrochemical process that causes deterioration of metal surfaces exposed to air, water, or excessive humidity.

Counterflashing A removable sheet-metal flashing that laps over membrane flashing to prevent water from penetrating between the membrane and the wall.

Course A single horizontal layer of units in a masonry wall.

Coursed rubble Irregularly shaped and sized stone laid with periodically aligned bed joints.

Crane A type of construction equipment used to hoist and place heavy building components or materials during construction.

Crawl space Air space between an elevated ground floor and the ground.

Creep Permanent deformation of a component under sustained loads, generally of concern in concrete and wood.

CRF See *condensation resistance factor*.

Cricket A pyramidal formation on a roof to divert water to drains or on an easily drained area of the roof.

CSI Construction Specification Institute.

CSMU See *calcium silicate masonry unit*.

Curtain wall Exterior wall cladding system suspended from or supported by the structural frame of the building.

D

Dampproofing A material applied to the exterior of a wall to resist the intrusion of capillary water.

Dead load Loads created by the weight of building components.

Decibel (dB) A measure of the loudness of sound.

Deep foundation A foundation element that extends deep below the ground to reach bedrock or higher-bearing-capacity soil.

Deformation Change in the size or shape of a structural member as a result of an applied load.

Dew point The temperature at which the relative humidity of an air mass reaches 100% and the water vapor in air converts to (liquid) water, that is, condenses.

Diagonal brace A linear, diagonal stiffening element against lateral loads.

Die A tool with an orifice (hole) through which a soft, heated metal or plastic or a column of wet clay is pushed to give a long, continuous element.

Dimension lumber Lumber that ranges from 2 in. to 4 in. (nominal dimensions) thick.

Dimension stone Stone that has been fabricated to specific dimensions, texture, and finish for use in buildings.

Dimmable glass A glass that changes from a transparent to a translucent or opaque condition when exposed to sun (photochromic glass) or electrical current (electrochromic glass).

Dome A curved roof structure over a round or rectangular space.

Double-skin glass curtain wall A glass curtain wall assembly composed of two layers of glazing separated by 1 to 5 ft of air space, also called a double-skin facade or bioclimatic glass curtain wall.

Double-strength (DS) glass Flat glass that is $\frac{1}{8}$ in. thick.

Double tee A precast concrete floor or roof element to span long distances.

Dowel A steel or wood pin used with an adhesive to connect adjacent pieces of wood; a steel reinforcing bar that projects from a foundation to form a splice with reinforcing bars in a concrete column or wall above the foundation.

Drainage wall A cavity wall with an air space between the exterior cladding and the inner backup wall, allowing water to drain out through weep holes.

Drilled pier A reinforced-concrete column constructed by drilling a round hole (of required diameter) in the soil, reinforcing it, and filling the hole with concrete. Drilled piers are used as foundation elements where near-surface soil is unsuitable for building foundations.

Drip edge Perimeter or edge flashing with an angled lip to keep water away from a vertical surface below.

Drop panels A widening of the underside of a concrete slab at a column location.

Dry glazing Use of preformed compression gaskets to seal the glass against the metal frame of a window or metal-glass curtain wall.

Drywall See *gypsum board*.

Ductile material A material that produces large deformations under load before failure.

Dynamic joint A joint that allows a predetermined amount of unrestrained movement between components.

E

Eave The low end of a sloped roof.

Edge block A resilient material used to prevent the vertical edge of glass from touching the frame of a window or curtain wall.

Efflorescence A white deposit of water-soluble salts on an exterior masonry or concrete wall caused by the wetting of the wall.

Egress window A window in a habitable room of a dwelling that opens to a minimum size for use as a fire escape.

EIFS See *exterior insulation and finish system*.

Elasticity The ability of a deformed material to return to its original shape and size after the removal of a load, such as rubber.

Elastomeric A material that exhibits elastic (rubberlike) properties.

Elastomeric sealant A synthetic semiliquid material used to seal the joints between adjacent building components, which becomes an elastic material after curing.

Elevated slab An above-ground floor or roof slab, supported on columns and/or beams and forming an integral part of a structural frame.

Embodied energy Total amount of energy required to extract raw materials and manufacture a building material.

Emissivity A property of the surface of a material that governs its potential to emit radiation; the value lies between 0 and 1.0.

End-bearing pile A deep foundation element within the ground that transfers load to bedrock, in contrast to a friction pile that transfers load to the surrounding soil. See also *friction pile*.

Engineered fill Soil and/or aggregate with specified proportions and properties compacted into place so that the resulting product has predictable physical characteristics.

Engineered wood products Manufactured wood products rated for structural applications, such as plywood, oriented strandboard, or laminated veneer lumber; see also *manufactured wood products* and *industrial wood products*.

Epoxy A polymer-based adhesive.

Ethylene propylene diene monomer (EPDM) A stretchable polymeric membrane used as a single-ply roof membrane.

Expanded polystyrene Open-cell foamed plastic insulating material formed into rigid boards.

Expansion anchor An anchor that allows expansion and contraction while connecting the vertical framing members of a glass curtain wall to the building structure.

Expansion joint A narrow space between two building components that allows their unrestrained expansion and contraction.

Exposed aggregate A type of concrete finish with coarse aggregate exposed at the surface.

Exposed ceiling A ceiling where all structural components and mechanical and electrical services are left exposed to the area below.

Exposure The exposed portion of lapped roofing felt or shingles.

Exterior insulation and finish system A stuccolike exterior finish that includes a layer of foam insulation, fiberglass reinforcing mesh, and one or two coats of a polymer-based finish; also called synthetic stucco.

Extruded brick Wet clay extruded through a die and cut to size before drying and firing. See also *molded brick*.

Extruded polystyrene Closed-cell foamed plastic insulating material formed as rigid boards by an extrusion process.

Extrusion See *die*.

F

Face shell Longitudinal walls of a concrete masonry unit.

Facing brick Brick used in an exposed exterior masonry wall, controlled for dimensional variations, warpage, and durability.

Factor of safety A safety margin added to structural calculations to account for our imprecise knowledge of material strength, loads, and theories pertaining to structural analysis and design, defined as the actual strength of a component divided by the strength required to carry the load.

Ferrous metal A metal that contains mainly iron.

Ferrule A threaded cylindrical sleeve that accepts a bolt, typically embedded in a precast-concrete member.

Fiberboard A product made from wood fibers (softwood or hardwood). In terms of increasing density, particle board, medium-density fiberboard (MDF) and high-density fiberboard (hardboard) are three types of fiberboard commonly used.

Fiberglass Mineral fiber spun from glass.

Fibrous insulation An insulating material that has a high R-value due to the air contained between the fibers.

Fill Soil or aggregate that fills the area under the foundations or between the exterior of a foundation and the boundaries of an excavation. See also *engineered fill and backfill*.

Filter fabric A porous filter fabric for filtering out silt, sand, or debris in a protected membrane roof, French drain, or foundation drain.

Finger joint A method of joining short lengths of lumber using interlocking "fingers" at the end of each piece and gluing the members together.

Finish coat The last layer of material that provides the final color and texture on a surface, such as the portland cement-based layer on stucco or the polymer-based layer on the exterior insulation and finish system.

Fire-rated glazing A glazing system that will resist a standard fire for the measured duration.

Fire rating The ability of a building assembly to endure fire, measured in hours or minutes of time and determined from standardized full-scale tests.

Fire-resistance rating See *fire rating*.

Fire-retardant lumber Wood that is pressure treated with chemicals to increase its fire resistance.

Fire-stopping A noncombustible material used to seal the space around a penetration or joint in a fire-rated wall, floor, or roof.

Fixed window A window unit where the glass is permanently fixed into the frame.

Flame finish A type of finish on a stone surface (generally granite) using a torch on wetted stone to break the surface, creating a rough, slip-resistant finish; also called thermal finish.

Flame spread index (FSI) A measure of the rate at which flames spread on the surface of an interior finish.

Flange Top and bottom components of an I-section or C-section steel beam.

Flashing A flexible metal or plastic used at roof terminations, edges, or penetrations to increase the strength and water resistance of the roof; a flexible metal or plastic sheet used as a drainage channel at the base of a cavity wall.

Flat glass Planar glass sheet (window glass), as opposed to glass block or other glass products.

Flat plate A reinforced-concrete slab of uniform thickness supported directly on columns.

Flat-sawn lumber See *plain-sawn lumber*.

Flat slab A reinforced-concrete slab, like flat plate, but the slab is thickened at the columns.

Flex anchor An L-shaped steel pin that connects to the GFRC skin with a bonding pad and is welded to the supporting light-gauge steel frame.

Float glass Flat glass manufactured using the float glass process.

Floating The process of smoothing a freshly placed concrete surface after it has been struck (leveled). See also *striking*.

Floating floor A floor assembly consisting of a resilient underlayment to isolate the finished floor from the subfloor; can also be a double floor with an intervening air space.

Fluid-applied roof membrane A combination of sprayed polyurethane foam insulation topped by a fluid that cures to a membrane.

Flush joint Troweled masonry mortar joint, where the mortar is finished flush with the masonry face.

Flux A material added to the primary material to lower the primary material's melting-point temperature, saving energy.

Fly ash A waste product obtained from the combustion of coal in a thermal power plant (a pozzolanic material), used as a concrete admixture.

Flying form A large, prefabricated formwork for concrete floors, which can be lifted (flown) into position by a crane and reused multiple times.

Foamed concrete See *insulating concrete*.

Foamed plastic Plastic insulating material that contains small volumes of air or another gas.

Footing The bottom portion of a foundation resting directly on the supporting soil with an area larger than that of the supported wall or column.

Form ties Specially shaped steel wires that are used to connect and separate opposing panels of formwork for a concrete wall.

Formwork Temporary support system for fresh concrete to give it the desired shape (form) until it cures to hardness.

Frame structure Building structure that is composed of columns and beams, called a skeleton frame in the case of a steel frame structure.

Framing plan Architectural plan that delineates the organization and dimensions of columns, beams, and load-bearing walls (if any).

Freeze-thaw A cycle of freezing and thawing of water within water-absorptive materials, such as soil, masonry walls, or concrete.

Friction pile A load-bearing pile that carries load by friction developed between the surface area of the pile and the soil. See also *end-bearing pile*.

Fritted glass Glass made semiopaque or opaque by the application of patterns of tiny dots or lines of ceramic material on one surface of flat glass.

Frog A small depression in a molded brick.

Frost line The depth of soil below which groundwater will not freeze.

Furring Narrow wood or formed sheet-metal sections applied to a wall or ceiling, used for supporting and attaching a finish material on the wall.

G

Gable Triangular portion of an exterior wall between the eave and the ridge in a gable roof.

Gable roof A roof with two sloping planes that meet at a point at the top, called a ridge.

Gable vent Passive exhaust ventilation unit located high on the gable end, used to exhaust attic air.

Galvanic corrosion Corrosion that occurs when two dissimilar metals are in direct contact with each other.

Galvanizing Method of coating steel with zinc to provide a corrosion-resistant (sacrificial) coating.

Gasket A shaped piece of resilient material that provides a weatherproof seal between the glass and the frame in a window or metal-glass curtain wall. See also *dry glazing*.

General contractor A contractor who has the final responsibility for the construction of the project including site safety, supervision, and coordination of the work of all subcontractors.

Geodesic dome A hemispheric dome formed by short, crisscross linear members that run along great circles of the sphere, creating triangles or polygons on the surface of the dome.

Geotechnical report A document prepared by a geotechnical (soils) engineer that identifies and describes the properties of soil and the underlying geology of the building site.

GFRC Glass fiber–reinforced concrete.

GFRP Glass fiber–reinforced plastic.

Girder A large beam (also called a primary beam) that carries the loads from secondary beams or joists to columns in a frame structure.

Glass block See *glass masonry unit.*

Glass fiber–reinforced concrete Glass fibers reinforce a mix of portland cement, sand, and water that is sprayed on formwork to form a panel that is integrated with a light-gauge steel frame and used in curtain wall assemblies.

Glass fiber–reinforced plastic A plastic material reinforced with fiberglass, molded to the desired shape.

Glass masonry unit A hollow glass unit used in non-load-bearing wall applications to provide a translucent wall.

Glazing An assembly of flat glass and its supporting frame.

Glazing compound A semisolid compound mastic, which cures to hardness, used to bed small panes of glass in a window frame; not commonly used in contemporary buildings.

Glue laminated Lengths of dimension lumber, glued and laminated together to create a structural member of a large cross section.

Glulam See *glue laminated.*

GMU Glass masonry unit.

Gradation Distribution by size of soil particles within a soil mass; also applies to aggregates in a concrete mix.

Grade beam A reinforced-concrete beam constructed at ground level.

Graded lumber Lumber with a grade stamp.

Grade stamp Stamp affixed by a grading (inspection) agency on lumber or a wood panel that describes its in-service performance.

Grading Mechanically moving soil on a site to predetermined ground elevations.

Grain structure Pattern and density of fibers that compose wood.

Granite Strongest and densest of stones; it takes good polish and weathers more slowly than other stones; obtained from igneous rock.

Gravity load Building load caused by gravity and acting in the vertical direction; also called vertical load.

Green roof A landscaped roof.

Grille A grating or screen that protects an opening while allowing the passage of air.

Grout A high-slump (semiliquid) mortar that flows well enough to be placed or pumped between the voids in a masonry wall; a mortarlike, high-strength cementitious material for filling the space between the steel base plate of a steel column and the concrete footing; a cementitious material used to fill joints between ceramic or quarry floor tiles or panels after they have been laid.

Growth ring A nearly circular ring of wood fibers; a tree adds approximately one ring per year.

Guard rail A horizontal rail and associated supports to prevent people from falling from a stair or balcony.

Gunite See *shotcrete.*

Gusset plate A plate that connects two structural steel members, commonly used in a large steel truss.

Gypsum board A building panel faced on two sides by paper (or vinyl) with a gypsum core. Typically used on fire-rated interior walls. It is also called drywall, wallboard, or gypsum wallboard.

H

Handrail Diagonal rail at hand level adjacent to a stairway to provide support for people using the stairs, as distinguished from a guard rail.

Hardboard A product made from wood fibers and a resin binder under heat and pressure. It is denser than medium-density fiberboard (MDF). See also *fiberboard.*

Hardwood Wood obtained from trees that are deciduous and have broad leaves. See also *softwood.*

Head Top of a window or door.

Header The short face of a brick when laid in a horizontal position in a course of bricks, historically used to tie together two wythes of a thick brick wall; a beam (lintel) above a door or window opening in a wood frame or light-gauge steel construction.

Head joint Vertical mortar joint in a masonry wall. See also *bed joint.*

Headroom Minimum code-required clearance between a floor and an overhead projection or ceiling.

Heartwood The central portion of a tree trunk that no longer conducts nutrients, generally darker than sapwood. See also *sapwood.*

Heat-absorbing glass See *tinted glass.*

Heat-soaked glass A type of tempered glass obtained from a process that reduces (or eliminates) the possibility of spontaneous breakage of tempered glass during its service life. See also *tempered glass.*

Heat-strengthened glass A glass obtained by heating annealed (basic) glass to a high temperature and then suddenly cooling it; approximately twice as strong as annealed glass. See also *annealed glass* and *tempered glass.*

Heavy timber Sawn lumber with both cross-sectional dimensions greater than 5 in. (nominal).

Heavy-timber construction A construction type in which the floors, roofs, and structural frame are composed of heavy sections of wood without added fire protection.

Hip The edge of a hip roof where adjacent slopes meet; shown as a diagonal line in the plan of the roof.

Hip roof A roof formed by four sloping planes that intersect to form a pyramidal or elongated pyramidal shape.

Hollow-core door Wood or metal veneer placed on both sides of a frame to build a door that is partially or almost entirely hollow within.

Hollow structural section (HSS) Square or rectangular tubular steel section used as columns or beams in a steel-frame structure or as components of a steel truss.

Honed finish A type of smooth finish on stone or metal created by using abrasives.

Horizontal diaphragm A structural engineering term that refers to the floors and roof in a building when they function as part of the lateral load-resisting system.

Hydrated lime Calcium hydroxide, produced by combining quicklime and water to produce a relatively benign lime, used in powder form in masonry mortar. See also *slaked lime.*

Hydration Chemical reaction between portland cement and water that causes the mix to become hard.

Hydraulic cement A cement (glue) that, after setting, does not react chemically with or dissolve in water, such as portland cement.

I

IBC International Building Code.

Ice dam protection membrane A self-adhering waterproof membrane that prevents water from backing up under roof shingles when an ice dam forms at the eave.

IGU Insulating glass unit.

IMG Intumescent multilaminate glass

Impact insulation class (IIC) Measure of the ability of an assembly to resist the transmission of structure-borne sounds.

Impact sound Structure-borne sound produced by an impact on a building component.

Impact wrench A tool for tightening bolts and nuts through rapidly repeated torque impulses produced by electric or pneumatic power.

Industrial wood products Manufactured wood products used for nonstructural applications, including particle board, medium-density fiberboard (MDF), and high-density fiber-board (HDF). See also *manufactured wood products* and *engineered wood products*.

Infrared radiation Long-wave radiation emitted by objects at low temperature.

Infrastructure Basic organizational systems that provide services to a building, including roads, power, water, and electricity.

Initial rate of absorption (IRA) A measure of the ability of clay bricks to absorb water, used to determine if bricks need to be wetted before being laid.

Inside glazed Glazing system in which the glass is set into the frame from the inside of a building. See also *outside glazed*.

Insulated metal panels Metal panels consisting of polyurethane foam sandwiched between and bonded to two metal sheets, used in curtain wall applications.

Insulating concrete Lightweight concrete consisting of portland cement, water, and expanded aggregate (perlite or vermiculite), primarily used as low-slope roof insulation. A type of insulating concrete (called foamed concrete) does not contain aggregate but does contain air particles. A fire-resistant insulation material for roofs and floors.

Insulating glass unit A sealed assembly of two layers of glass separated by an air- or gas-filled chamber. The assembly has a higher R-value than a single sheet of glass.

Insulation See *thermal insulation* and *sound insulation*.

Integrated project delivery (IPD) A project delivery method in which all people connected with the design and construction of the building, including the owner and fabricators of assemblies, collaborate as a team in a no-blame contractual agreement as if they all belonged to the same organization. The profits are generally shared at the completion of the project by team members on a predetermined basis.

Interior finish class Rating of interior finish materials as Class A, B, or C based on the flame-spread index (FSI) and the smoke-developed index (SDI).

Intumescent paint A paint that swells when exposed to heat, creating an insulating layer that protects steel from short-term exposure to fire.

Inverted roof See *protected membrane roof*.

Inverted T-beam A precast concrete beam with flanges at the bottom, generally used to support double-tee concrete floors.

Isolation joint A joint in a concrete slab-on-ground that penetrates the entire thickness of the slab, used to separate the slab from the structure (walls and columns).

Isotropic material A material that has the same properties in all directions, such as steel. See also *anisotropic material*.

J

Jack rafter A shorter rafter (than a common rafter) that joins to a hip or valley rafter.

Jack stud A stud of a shorter length attached to a longer king stud to support a header in the opening of a wood light frame wall.

Jamb Side of a window, door opening, or frame.

Joint compound Soft material used together with tape to finish a joint or cover nail dents in a gypsum wallboard assembly.

Joint cover Cover for an expansion or seismic joint in buildings to provide a continuous protective surface.

Joint reinforcement Continuous horizontal steel wire reinforcement laid in mortar joints of concrete masonry to control shrinkage cracks.

Joint sealants See *elastomeric sealants*.

Joist floor An elevated reinforced concrete slab with integral narrow ribs (like wood floor joists), also called a one-way joist floor or ribbed floor.

Joists Slender, closely spaced, parallel beams in a wood light (or light-gauge steel) frame floor.

Junction box Rectangular or circular metal or plastic box used to protect connections between electrical wires.

K

Kerf Slit cut into a surface, used to form a capillary break (drip edge) at the bottom edge of an exterior surface; a slit cut into building stone (used as wall cladding) to serve as a receptacle for a mechanical attachment system.

Key See *shear key*.

Keyway A gap between two adjacent precast-concrete floor units, typically reinforced and filled with portland cement grout.

Kiln A furnace used to dry materials such as green lumber; a furnace for drying and firing bricks; a furnace for making quicklime.

Kilopascal (kPa) A measure of load (force) in the SI system of units.

Knot An approximately circular formation of wood fibers formed where a limb branches from a tree trunk. A knot generally lowers the strength of wood.

Kraft paper Asphalt-treated paper that serves as a vapor retarder, commonly used as lamination on fiberglass insulation.

L

Laminated glass Two pieces of glass laminated under heat and pressure to a plastic interlayer to form a fused unit.

Laminated veneer lumber (LVL) Dried wood veneers laminated in layers, all oriented in the same direction, to form a large structural member.

Landing A horizontal platform between two flights of stairs.

Landing frame A structural frame that forms a landing in a prefabricated steel stair.

Lap splice A connection between two steel or wood members, where the ends of each member are overlapped and connected so that the two members function as one continuous member.

Lateral load Load that acts predominantly in the horizontal direction, such as wind or earthquake load or soil pressure on a basement wall.

Lath Expanded sheet metal attached to a backup wall and used as a mechanical key to bond and reinforce portland cement plaster (stucco).

LEED Leadership in Energy and Environmental Design.

Light-gauge steel framing A framing system that mimics wood light frame construction, but the elements are made of cold-formed, galvanized sheet steel.

Light-gauge stud Generally a C-shaped member made of light-gauge steel.

Light-transmitting plastic Transparent or opaque polycarbonate or acrylic sheet used as glazing in some limited situations.

Lime See *hydrated lime* and *quicklime*.

Limestone A sedimentary rock composed primarily of calcium carbonate and used as exterior and interior wall cladding.

Linoleum A resilient sheet or tile flooring made from linseed oil, organic resins, and fillers bonded to a fibrous backing.

Lintel A beam that spans over a door or window opening.

Lite A pane or sheet of glass.

Live load A type of gravity load that changes in magnitude and placement over time due to factors such as human occupancy or storage of roof repair or maintenance materials, subdivided into floor live load and roof live load. See also *dead load*.

Load-bearing-wall A wall that supports superimposed gravity loads, such as from floors and the roof. See also *non-load-bearing wall*.

Longitudinal bars Steel reinforcing bars placed in the long direction of a reinforced-concrete beam or column.

Louvers Fixed or operable, closely spaced, angled slats attached to a frame to direct the passage of air or light.

Low-emissivity (low-E) coating A surface coating that reflects most of the long-wave radiation.

Low-emissivity glass A glass treated with a low-E coating, called low-E glass.

Low-emissivity (low-E) material A material that is an efficient reflector (poor absorber) of long-wave radiation (heat), generally obtained through a low-E lamination (such as aluminum foil) or a low-E coating.

Low-slope roof A roof with a slope less than 3:12.

Lumber Solid wood products derived directly from logs by sawing and planing only, with no additional machining.

LVL See *laminated veneer lumber*.

M

Machine grading A method of grading lumber using a machine, also called machine stress-rated lumber (MSR), in contrast with the more commonly used method of visual grading.

Machine stress-rated (MSR) lumber See *machine grading*.

Malleability A property of metals that indicates their ability to be formed to shape by hammering, bending, forging, pressing, rolling, and so on.

Manufactured wood products Any of a variety of wood products made by bonding smaller pieces of wood veneers, fibers, strands, wafers, or particles to produce a composite wood material. See also *engineered wood products* and *industrial wood products*.

Marble A metamorphic rock geologically formed from limestone under high pressure and heat.

Masonry Materials such as brick, stone, concrete masonry units (concrete blocks), and glass masonry units that are stacked and adhered using mortar.

Masonry cement A preblended mix of portland cement, lime, and/or pulverized limestone (typically manufacturer specific) used in masonry mortar in place of portland cement and lime.

Masonry grout A high-slump concrete used to fill the voids in a masonry wall.

Masonry unit Single brick, concrete (or glass) block, or stone used in masonry construction.

MasterFormat The standard organizational format for construction specifications (note the absence of space between *r* and *F* in ”MasterFormat”).

Mat foundation A type of concrete foundation where one large, combined footing is used for several columns and load-bearing walls, often for the entire building. A concrete slab-onground used as a foundation for light frame buildings is the simplest type of mat foundation.

MDF An acronym for medium-density fiberboard. It is made from wood fibers and resin binder under heat and pressure. It is denser than plywood and is commonly used for cabinets and other furniture. See also *fiber board*.

Means of egress The route by which one exits a building in the case of a fire.

Metal A highly refined (generally solid) material that is typically hard, malleable, ductile, and capable of carrying an electrical current. Steel, copper, and aluminum are commonly used metals in building construction.

Metal panel roof A roof covering composed of thin sheets of metal, laid over rigid insulation and mechanically attached to the roof structure.

Mil A unit of thickness typically used to express the thickness of sheet plastic or sheet metal. 1 mil = 1/1,000 in.

Mission tile A clay or concrete tile with a half-barrel profile.

Model code Building code developed and updated regularly by an independent agency and adopted and adapted for use by federal, state, or local jurisdictions. The International Building Code, International Residential Code, and International Plumbing Code are examples of model codes.

Modified bitumen A type of polymer-modified bitumen (generally asphalt) used in making modified-bitumen roof membranes.

Modular brick The most commonly used size of extruded brick (4 in. × $2\frac{2}{3}$ in. × 8 in. nominal dimensions).

Modulus of elasticity A property of a material that measures its stiffness against deformation under loads.

Moisture movement Expansion or contraction of a material that occurs as a result of a changing moisture content.

Moisture retarder A membrane that retards (prevents) liquid water from passing through.

Molded brick A brick formed by pressing small clumps of wet clay into molds. See also *extruded brick*.

Moment connection A connection between a beam and its support (e.g., a wall or column) that transfers the bending of the beam to the support, or vice versa.

Mortar A mixture of portland cement, lime, sand, and water used to bond masonry units; cementitious mixture used to adhere tiles to a subfloor.

Mortar-capturing device A synthetic mesh located just above the flashing in the air space in a brick veneer wall used to prevent mortar from clogging the weep holes.

Mortar cement A preblended (typically manufacturer-specific) mix of portland cement, lime, and admixtures.

Mortar joint The layer of mortar placed between masonry units, generally about $\frac{3}{8}$ in. thick.

Movement joint Same as *dynamic joint*.

Mud sill See *sill plate*.

Mullion A vertical member in a metal-glass curtain wall; a vertical member between two adjacent windows or doors.

N

Nail Metal fastener made from a wire with a pointed tip (bottom) and a (generally flat) head.

Nailing flange Continuous flat metal or plastic extrusion from a window frame used to nail the unit to the exterior of a wall opening in a wood frame building.

Nail plate A metal plate with several sharp, flat, naillike projections.

Neoprene A synthetic rubber primarily used in glazing gaskets.

NFRC rating Window-performance rating system developed by the National Fenestration Rating Council (NFRC).

Noise-reduction coefficient (NRC) A measure of the ability of a material to absorb sound; the value lies between 0 and 1.0.

Noncombustible A material that will not ignite when subjected to an open flame or high temperature. See also *combustible*.

Non-load-bearing wall A wall that does not support floor or roof loads.

Nonmovement joint Same as *static joint*. See also *dynamic joint* or *movement joint*.

Nosing The leading edge of a tread of a stair.

Nylon A versatile polymer whose fibers are used in carpet and fabrics; also produced in sheets or molded into fittings used in mechanical devices.

O

Occupancy load Floor live load based on its occupancy.

One-way joist floor See *joist floor*.

One-way slab An elevated reinforced concrete slab where most of the load on the slab is carried to the supporting beams in one direction; a four-sided, supported rectangular slab whose length is greater than or equal to twice its width.

Open-web steel joist A standardized, prefabricated steel parallel chord truss used to span between beams, larger joists, or trusses.

Operable window A window unit that opens to allow the passage of air, sound, and so on. See also *fixed window*.

Organic soil A soil containing decayed plant material.

Oriented strandboard A wood-based panel made by gluing several layers of wood strands under heat and pressure so that the adjacent layers are oriented in opposite directions.

OSB See *oriented strandboard*.

Outside glazed Glazing system in which the glass is set into the frame from the outside of a building.

Oxidation Chemical weathering process by which the source material combines with atmospheric oxygen, generally leading to the material's degradation, such as oxidation of iron or steel, called corrosion, or rusting.

P

Pan Glass-reinforced plastic pans used as an economical formwork for one-way concrete joist floors.

Pane A sheet of glass.

Panel A sheet of plywood, oriented strandboard, particle board, and so on; a prefabricated building component whose surface dimensions are much greater than its thickness, such as a curtain wall panel.

Panel door A wood door constructed by inserting solid wood panels or glass panes in horizontal and vertical frame members (rails and stiles, respectively).

Panelized stone cladding Multiple stone slabs attached edge to edge to a prefabricated steel-frame work, which is then attached to the exterior of a steel- or concrete-frame building.

Panel points Points on a truss where members of a truss connect.

Parallel-strand lumber Manufactured wood product composed of narrow strands of veneered lumber glued together, all oriented in the same direction to form a member of large cross section.

Parapet Portion of an exterior wall that extends above the roof line.

Parging A thin, rough (unfinished) coat of portland cement plaster on a masonry wall. The purpose of parging is to increase the water resistance of the wall and to provide a smoother wall surface. Parging is not intended to be finished plaster.

Partition wall A non-load-bearing interior wall that separates spaces but does not carry floor or roof loads.

Patching compound A liquid or semisolid compound that can be troweled on to correct surface irregularities.

Paving bricks Bricks used for paving, graded for abrasion resistance and freeze-thaw damage.

Permanent formwork Material used as formwork (typically, metal deck) and retained as a permanent part of a reinforced-concrete floor slab.

Permeability Property of a material (e.g., soil) or assembly that allows water or water vapor to pass through.

Permeance A measure of the rate at which water vapor flows through a material or assembly.

Pier A relatively short column or a deep vertical foundation element (typically of cast-in-place concrete). A pier is not the same as a drilled pier (see *drilled pier)*.

Pilaster A column formed by thickening an area of a masonry or concrete wall.

Pile Driven or drilled long, slender foundation element.

Pile cap A concrete cap that transfers foundation loads to multiple piles beneath.

Placing concrete The operation of pouring fresh concrete from a concrete mixer into the formwork.

Plain concrete Concrete without steel reinforcement.

Plain masonry A masonry wall without (vertical) steel reinforcement.

Plain-sawn lumber Lumber produced by sawing a log in one or two directions only. The grain pattern varies from nearly parallel to the wide face to perpendicular.

Planing Operation that uses high-speed knives to smooth the surface of rough-sawn lumber.

Plaster Pastelike cementitious material that, when applied to the surface of a wall or ceiling, cures to a hard surface.

Plasterboard Specific type of gypsum board used as a substrate for plaster.

Plastic A synthetic material composed of polymers that can be molded or shaped when soft; it cures into a rigid or semielastic form and does not return to its original shape after being deformed.

Plate girder A heavy steel beam fabricated from steel plates.

Platform frame One of the two types of wood light frame constructions, the other being a balloon frame. In a platform frame, the studs are one floor high and extend between adjacent floors or from the floor or roof. See also *balloon frame*.

Plywood A panel made from multiple thin layers of wood veneer adhered with glue under heat and pressure so that the grain direction of a veneer is perpendicular to that of the adjacent veneer.

Pointing Raking an existing (generally defective) masonry mortar joint to sufficient depth and then finishing it with new mortar.

Point-supported curtain wall Mullionless glass curtain wall with glass panes supported at its corners by a metal connector and glass panes sealed at vertical and horizontal joints with a sealant. See also *spider connector*.

Polished finish A type of stone finish, attained by buffing to give a reflective sheen.

Polyethylene A polymer, typically used in sheets as a vapor retarder.

Polyisocyanurate Closed-cell foamed plastic insulating material, sandwiched between two facing layers, available as rigid (flat or tapered) boards, typically used as roof insulation.

Polypropylene Synthetic fiber, commonly used in carpets and fabrics.

Polyvinyl chloride (PVC) A versatile thermoplastic polymer, used in single-ply roof membranes, rigid plastic pipes, and so on.

Porosity The property of a material that allows liquid or air to pass through.

Portland cement A noncombustible hydraulic cement produced by burning limestone and clay. See also *hydraulic cement*.

Portland cement plaster Multilayered application of a cementitious mix of portland cement, lime, sand, and water to a thickness ranging from $\frac{5}{8}$ in. to 1 in., commonly used on exterior walls.

Posttensioning Subjecting a concrete or masonry member to compressive stresses by tensioning high-strength steel strands (wires) after the concrete has developed sufficient strength.

Pour To cast or place concrete; an increment of concrete placement carried out without a long interruption.

Pour stop An L-shaped steel member welded to a steel spandrel or edge beam to stop fresh concrete from flowing beyond the edge of a floor or roof.

Pozzolanic reaction Reaction between lime and amorphous silica (such as in fly ash, silica fume, etc.) that converts the mixture into a hydraulic cement. See also *hydraulic cement*.

Precast concrete Concrete members typically cast in a precasting plant and transported to the construction site for erection. Precasting can also be done at the construction site, such as with concrete tilt-up walls.

Precast, prestressed concrete A precast-concrete member that has been subjected to compressive stresses by tensioning high-strength steel wires before casting concrete for the member.

Preformed tape An elastomeric material (available in rolls) that provides a seal between the glass and the supporting frame in a window or metal-glass curtain wall.

Pressure-equalized wall A drainage wall where the air space between the exterior cladding and the backup wall is at the same pressure as the outside air so that water penetration through the wall is minimized.

Pressure-treated wood Wood into which preservatives have been pressure injected to retard termite infestation and fungal decay. Using a different preservative, the pressure treatment can also be used for increasing the fire resistance of wood.

Prestressed concrete See *precast, prestressed concrete*.

Pretensioning Same as prestressing. See also *posttensioning*.

Primary reinforcement Steel reinforcement in a one-way concrete slab oriented in the direction that carries most of the loads; see also *one-way slab*.

Primer A liquid that improves the adhesion of a sealant or paint to the substrate.

Probability of breakage The probability that a pane of glass will break unpredictably, measured as the number of broken panes (out of 1,000) when the panes are subjected to a given load.

Protected membrane roof (PMR) A roof membrane directly attached to the roof deck and covered with rigid insulation held in place by ballast.

PSL See *parallel-strand lumber*.

Punched window A window surrounded by opaque portions of the wall.

Punch list A list of outstanding problems that must be corrected before the architect certifies that the building is complete.

Putty See *glazing compound*.

Pylon A heavy vertical support member, commonly used in suspension bridges.

Q

Quarry An excavation from which stone is obtained.

Quarry tile A clay floor tile, generally unglazed.

Quarter-sawn lumber Lumber produced by cutting the log radially into four quarters and then sawing it along radial lines.

Quicklime Lime obtained by heating limestone. Chemically, it is calcium oxide, which is a fairly caustic substance and is, therefore, not used in construction. When quicklime is mixed with water, it becomes calcium hydroxide, also called hydrated lime. Hydrated lime is used in building construction.

R

Racking Angular deformation of a structure under lateral loads, such as the deformation caused by a horizontal force on a book rack.

Radiant barrier Layer of material that slows the transmission of heat due to its low emissivity. Aluminum foil is a commonly used radiant barrier.

Radiation Emission of electromagnetic waves by an object. All objects emit radiation at all times.

Rain screen wall Same as *pressure-equalized wall*.

Rake Sloping edge of a gable roof.

Raked joint Tooled, inset masonry mortar joint that creates a strong shadow line.

Random rubble Irregularly shaped and sized stone laid in a random pattern in a wall.

Rebar An abbreviation for reinforcing bar (a deformed steel bar used as concrete reinforcement).

Reciprocating saw Fixed or handheld saw that uses a linear blade, which moves horizontally and/or vertically at the same time.

Reflective glass A glass that reflects incoming visible radiation due to a very thin metal oxide coating on one surface.

Reglet A slot in a concrete or masonry wall in which a flashing or roof membrane is inserted and held in place by inserting a compressible material in the slot.

Reinforced concrete Concrete with integral steel reinforcing bars.

Reinforced masonry A masonry wall with vertical reinforcing bars; see also *plain masonry*.

Reinforcement cage A preassembled unit of reinforcing bars used in concrete members.

Relative humidity Amount of water vapor present in the air, measured as a percentage of the maximum water vapor the air can hold at the same temperature.

Reshoring A method of supporting a concrete floor after the formwork has been stripped and before it has gained the strength required to support the superimposed loads.

Resilient channel Light-gauge steel channel used for attaching gypsum boards so that the gypsum boards are acoustically decoupled from the backup wall on which the channel is attached.

Resilient flooring Synthetic flooring material, such as linoleum, vinyl, or rubber tiles or sheets, that returns to its original shape after being compressed by impacts caused by walking, dropped objects, and so on.

Resinous flooring A liquid-applied flooring material that dries to form a thin, strong floor surface; also called epoxy flooring. Includes epoxy-based terrazzo.

Ribbed floor See *joist floor*.

Ribbed slab A concrete slab that is stiffened by the edge and interior ribs (beams) in both directions, used as an elevated or ground-supported slab. Where the ribs are closely spaced (in both directions), it is also called a waffle slab or two-way joist floor.

Ridge beam A structural beam that supports the top ends of roof rafters at the ridge line and forms a triangular shape without creating lateral thrust.

Ridge board A nonstructural board used to align and join rafters at the ridge line of a sloping roof.

Ridge line The line of intersection of two oppositely sloping roof planes.

Ridge vent Passive air-exhaust unit located along the ridge of a sloping roof to exhaust attic air.

Rigid connection See *moment connection*.

Rigid insulation Rigid boards of foamed, granular, or cellular materials.

Rim joist Outer joist that surrounds the wood frame floor structure.

Riser Vertical component of a stair.

Roof deck A load-bearing surface on which a roof membrane is attached.

Roofing felt Organic (typically paper-based) or inorganic (typically fiberglass) fibers pressed into a thin, flat sheet and saturated with bitumen (asphalt or coal tar).

Roof membrane The entire waterproofing layer on the roof.

Rubber flooring Rubber sheets or tiles used as floor finish.

Running bond Masonry bond pattern that staggers the units in each course, creating staggered head joints.

R-value See *thermal resistance*.

S

Safety glass Glass that can resist impact (per the safety glass test standard) and, upon breaking, falls into pieces that are small and blunt enough not to cause injury.

Safety margin See *factor of safety*.

Sapwood The outer portion of a tree trunk that conducts nutrients, typically lighter in color than heartwood. See also *heartwood*.

Sash The (operable) part of a window, which holds the glass.

SBS See *styrene butadiene styrene*.

Scab A small piece of lumber nailed to two butt-jointed lumber members to give them continuity.

Scaffold An elevated temporary platform (movable or unmovable) on which workers (such as bricklayers, plasterers, and painters) stand to perform their work. The term scaffolding is used for a system of scaffolds.

Scratch coat First of two base coats in stucco.

Seasoning Process of drying of lumber until the moisture content reaches the desired percentage.

Secondary reinforcement Reinforcement in a one-way concrete slab placed perpendicular to primary reinforcement. See *one-way slab*.

Security glazing Glazing system that can withstand various levels of assault from handheld weapons, ballistic weapons, and so on.

Seismic joint Continuous joint that divides large or complex buildings into smaller buildings that can move independently of each other to reduce damage from an earthquake; generally wider than a building separation joint. See also *building separation joint*.

Self-drilling fastener A fastener that drills its own hole.

Self-furring metal lath A metal lath with dimples that holds the lath away from the substrate to which the lath is applied, allowing the plaster to go through the lath and embed the lath in the plaster.

Setting block A strong, resilient block that supports the glass pane in its frame and cushions it against damage; located at the lower edge of a glazing pocket.

Setting material A material used to adhere ceramic and stone floor tiles to the subfloor.

Settlement Natural compaction of a soil mass, or shifts in a structure resulting from compaction or instability of soil underlying the foundation.

S4S A lumber member surfaced on all four sides.

Shading coefficient Solar heat gain through a glass divided by the solar heat gain through clear $\frac{1}{8}$-in.-thick glass.

Shaft A continuous vertical enclosure around stairs, elevators, ducts, pipes, and so on.

Shear Stress that acts tangential to the cross section of a member, causing various planes of the member to slide relative to each other.

Shear block A small metal block used to attach horizontal rails to mullions in a metal-glass curtain wall.

Shear key A continuous groove in the first concrete pour that is filled with concrete during the second pour to prevent differential movement between the two elements, such as between two adjacent concrete slabs or a foundation wall and its footing.

Shear stud A short, headed steel rod welded to the top of a steel beam (girder or joist) that is embedded in the concrete slab over the beam so that the beam and the slab act as one structural unit.

Shear wall See *vertical diaphragm*.

Sheathing A panelized material applied to the exterior surfaces of wood or light-gauge steel frame members to add rigidity to the frame and to serve as a base for (wall) cladding or roofing.

Shed roof A roof that slopes to one side.

Sheet bracing A panelized material applied to a structural frame to prevent the frame from racking. See *racking*.

Sheeting Sheet piles; a thin sheet material such as polyethylene sheet.

Sheet pile Piles made of interlocking sheet steel driven into the ground to support an excavation.

Shelf angle Steel angle attached to a spandrel beam or a load-bearing wall to support masonry veneer.

SHGC See *solar heat-gain coefficient*.

Shim A thin, flat piece of metal, plastic, or wood placed between two components to adjust their relative positions during construction.

Shingles Small roofing units of asphalt-treated felts, wood, metal, concrete, or clay tiles, slate, and so on, that lap over each other to waterproof steep roofs.

Shop drawings Detailed drawings of a building component developed by its fabricator based on construction drawings and specifications.

Shores Temporary vertical or inclined supports used in concrete formwork or excavation.

Shotcrete Concrete mix that is deposited through a nozzle at high pressure in combination with a stream of compressed air; also called gunite.

Siding Exterior wall-finish material applied to a wood light frame or light-gauge steel-frame building.

Sieve An open-top container with a wire mesh bottom used for screening particles. Sieves are used in laboratories for analyzing the particle size distribution of soils and concrete aggregates.

Sill Bottom horizontal portion of a window, the exterior part of which is typically sloped away from the window.

Sill plate The bottom, horizontal member in a wood light frame (or light-gauge steel) wall that is directly in contact with the foundation.

Simple (shear) connection A connection between a beam and its support (e.g., a wall or column) that allows the beam to bend without transferring its bending to the support.

Simply supported beam A single-span beam with simple connections at both supports.

Single-ply roof (SPR) membrane A single-layer synthetic roof membrane.

Single-strength (SS) glass A $\frac{3}{32}$-in.-thick flat glass.

SIPS See *structural insulated panels*.

Site-cast concrete Concrete cast in the position where it will remain in the final structure.

Slab-on-grade A concrete slab that is supported directly on the ground.

Slab-on-ground Same as *slab-on-grade*.

Slaked lime Same as *hydrated lime*

Slag A noncombustible waste product obtained from the manufacture of iron in a blast furnace, commonly used as aggregate on built-up roofs.

Slag wool Slag converted to fibrous insulation.

Slip connection A connection that allows movement between connected elements in at least one direction.

Slip-critical connection A connection between two structural steel members bolted together in which the load on one member is transferred to the other member mainly by friction.

Slump test A test that measures the workability of fresh concrete by filling a cone-shaped mold with concrete, removing the mold, and measuring the height to which the concrete settles below its original height.

Slurry A liquid mixture of an insoluble material and water, such as portland cement and water (called portland cement slurry) or bentonite clay and water (called bentonite slurry).

Slurry wall A method of constructing a reinforced-concrete basement wall by temporarily stabilizing the wall excavation with bentonite slurry and then pumping concrete into it. As the concrete is pumped, the slurry is displaced.

Smoke-developed index (SDI) A measure of the visibility through smoke in a building fire.

Smooth, off-the-form concrete The smooth finish on concrete revealed when formwork is removed, without any further surface treatment.

Snap tie A steel wire tie used in formwork for concrete walls.

Soffit The underside of a horizontal building element, such as that of a roof overhang or of a stair.

Soffit vent Air intake ventilation unit located in the soffit of a roof overhang.

Softwood Wood obtained from trees that have thin conical leaves and are typically evergreen. See *hardwood*.

Solar heat-gain coefficient Solar heat transmitted through a glass divided by the solar heat that falls on the glass.

Solid-core door Flush wood or metal veneers laminated to both sides of a solid interior, in contrast to a hollow-core door.

S1S2E A lumber member surfaced on one side and two edges.

Sound-absorbing material A material that absorbs more sound than most other materials.

Sound frequency The number of to-and-fro movements of air particles in 1 s in a sound wave.

Sound insulation A material that retards the transmission of sound.

Space truss A three-dimensional truss.

Spall Loss of the surface of a material, such as concrete or masonry, resulting from stresses caused by expansion or contraction of the material, such as during freeze-thaw cycles.

Spandrel area The area of the exterior facade of a building at the level of the spandrel beam.

Spandrel beam A beam that spans between columns on the exterior face of a frame structure.

Spandrel glass Glass (usually opaque) used in a metal-glass curtain wall in the spandrel area of the facade.

Spandrel panel A panel used in the spandrel area of a glass curtain wall.

Specific gravity Density of a material divided by the density of water.

Specifications Written technical description of materials and assemblies shown in construction drawings, organized in three parts: general, products, and execution.

Spider connector Four-pronged stainless steel connector used at the corner of four lites of glass in a mullionless glass curtain wall.

SPR See *single-ply roof (SPR) membrane*.

Spray-applied fire protection A mixture composed of portland cement, water, and mineral fibers (or lightweight aggregate) sprayed on a steel member to increase its fire resistance.

Stack bond Masonry bond pattern in which units are stacked vertically with continuous head joints.

Standing-seam metal roof Sheet metal roof panels joined by folding and/or interlocking seams.

Static joint Same as *nonmovement joint*.

Steel A strong, malleable metal (alloy of iron and carbon) used for structural and nonstructural shapes.

Steel decking A ribbed-sheet steel formed into panels, commonly used in floors and roofs.

Steep roof A roof with a slope greater than or equal to 3:12. See *low-slope roof*.

Stem wall A short foundation wall, generally used to form a crawl space below the ground floor of a light-frame building.

Step flashing Small lengths of metal sheets placed between roof shingles, used at locations where a sloping roof meets a wall.

Stick-built curtain wall A metal-glass curtain wall whose framing members are installed at the site member by member.

Stiffback A member attached to a frame to increase its stiffness.

Stirrup A loop or U-shaped steel reinforcement used to increase the shear resistance of a concrete beam.

Stone cladding Stone panels attached to a backup wall or curtain wall frame.

Stone honeycomb panel A lightweight panel made of thin stone veneer laminated to an aluminum honeycomb backing.

Stone masonry Stone laid with mortar unit by unit.

Storefront system Glazed facade, generally one or two stories high from the ground, with a framing system similar to that of a metal-glass curtain wall but with less stringent performance requirements.

Story drift Horizontal deflection of an upper-story floor with respect to a lower floor caused by lateral loads as a result of racking.

Strain Change in the dimension of a member divided by its original dimension.

Strands High-strength steel wires used in prestressing cables; thin wafers of wood.

Stress Internal resistance created by a member in response to an applied external force, expressed as force divided by the cross-sectional area of the member.

Stretcher Long face of a brick laid in its usual way in a wall.

Striking Leveling a freshly placed concrete surface, generally followed by floating. See *floating*.

Stringer See *carriage*.

Strip flooring Wood finish flooring made of long, narrow tongue-and-groove boards.

Stripping time Length of time between placing concrete and removing the formwork.

Strip windows An array of continuous window units placed side by side horizontally or vertically.

Structural composite lumber Manufactured wood products produced by gluing together longitudinally oriented wood veneers or stands.

Structural insulated panels Structural panels composed of rigid insulation glued on each side with oriented strandboard or plywood panels.

Stucco See *portland cement plaster*.

Studs Closely spaced vertical members that constitute a wood light frame or light-gauge steel frame wall.

Styrene butadiene styrene A polymer with rubberlike properties generally used as a modifier of asphalt, giving an SBS-modified roof membrane.

Subfloor Structural (rough) floor beneath a floor finish, such as carpet or floor tiles.

Substrate Underlying member on which other material is placed.

Substructure Below-ground portion of a structure, including the basement and foundation.

Sump A pit used to collect water, from which it is pumped out.

Superstructure Above-ground portion of a structure.

Surety bond A type of insurance required of a contractor by the owner to ensure that the obligations of the construction contract will be met.

Suspended ceiling A ceiling hung from the overlying floor or roof structure.

Sustainable Comprehensively addressing aspects of building design and construction in addition to health, safety, welfare, and aesthetic aspects that account for resource consciousness and stewardship of the environment and ensure that the needs of future generations are not compromised by today's generation.

Synthetic stucco Another name for exterior insulation and finish system (EIFS).

T

T&G See *tongue-and-groove*.

Tabular area Allowable area per floor as obtained from the building code table.

Tempered glass A glass obtained by heating annealed glass to a high temperature and then suddenly cooling it, which makes it four times stronger than annealed (basic) glass; used as safety glass because it breaks into pieces that are small and blunt enough not to cause injury.

Tendon The combination of high-strength steel strands, sleeves, and end anchorages used for posttensioning concrete.

Terrazzo A concrete-like material (binder, filler, and aggregate mix) that is poured over a subfloor in a thin layer, ground, and polished after it cures to form a floor finish.

Thermal break A section of a material with high thermal resistance epoxied between two parts of a material with low thermal resistance.

Thermal bridge A portion of a building envelope or a building assembly with a much lower thermal resistance than the rest.

Thermal capacity Ability of a building material or component to store heat.

Thermal conductor Material that conducts heat rapidly

Thermal finish See *flame finish*.

Thermal insulation A material or assembly that retards the flow of heat.

Thermal movement Changes in the dimensions of a material that occur as a result of a change in its temperature.

Thermal resistance (R-value) Measure of the ability of a building material or assembly to resist the flow of heat.

Thermal transmittance Inverse of thermal resistance.

Thermoplastic polymer A polymer that softens when heated and hardens when cooled.

Thermoplastic polyolefin A thermoplastic polymer used as a single-ply roof membrane.

Thermosetting polymer A polymer that will not soften when heated.

Thick-set mortar Thick bed of cementitious mortar on which floor tiles are set, used where the subfloor surface or the bottom of the floor tiles (or slabs) are irregular or too large for the use of thin-set mortar.

Thin-set mortar Method for attaching tile to the subfloor or underlayment using a thin layer of adhesive.

Threshold Floor surface immediately below an exterior door, typically sloped to the exterior.

Tieback A fastener that connects an exterior cladding to the supporting frame to resist lateral loads.

Ties Closed-loop reinforcement used in columns to prevent the buckling of longitudinal bars.

Tile Small, thin flooring or ceiling unit.

Tilt-up wall Reinforced-concrete wall, precast on the ground-floor slab of the building and lifted by a crane to its required position.

Timber See *heavy timber*.

Tinted glass A type of glass made by adding a metallic pigment during its manufacture.

Tongue-and-groove A joint between two members in which the edge of one member is milled with a groove and that of the other member is milled with a projecting tongue.

Tooled joint Joint in masonry mortar or sealant that is compressed by a specific tool.

Torched membrane SBS modified-bitumen roofing sheet adhered using an open-flame torch.

TPO See *thermoplastic polyolefin*.

Travertine A type of natural stone pitted with voids.

Tread Horizontal (walking) surface of a stair.

Tread pan A steel pan in a prefabricated steel stair that is later filled with concrete at the site to give a finished tread.

Tributary area Area of a building that contributes to the load on a building component.

Truss A structural member with triangulated, linear elements, typically used for large spans.

Trussed joist Parallel chord truss used as a floor joist.

Two-way joist floor See *ribbed slab* and *waffle slab*.

Two-way slab An elevated reinforced-concrete slab in which the load on the slab is carried to the supporting beams in both directions; a four-side-supported rectangular slab whose length is less than twice its width.

U

Ultraviolet radiation (UV) Short-wave solar radiation that can damage human skin and eyes as well as fade the colors of materials and art.

Ultraviolet transmittance A measure of the transmission of ultraviolet radiation through glass.

Underlayment (floor) A panel attached to the subfloor to create a smooth, rigid surface for the application of finish flooring.

Underlayment (roof) Water-resistant sheet applied as a second layer of defense under shingles in a steep roof.

Unit-and-mullion curtain wall Preassembled metal-glass curtain units attached to mullions that have already been attached to the building frame.

Unitized curtain wall Preassembled metal-glass curtain wall units attached to the building frame.

UVT See *ultraviolet transmittance*.

V

Valley A trough formed at the intersection of two adjacent sloping roofs.

Valley flashing Flashing material used in a steep roof valley to increase the water resistance of a valley trough.

Vapor drive analysis A numerical analysis that determines the amount of water vapor flow through the building envelope to ascertain the condensation potential.

Vapor pressure Pressure exerted by water vapor on the building envelope. Vapor pressure is independent of air pressure.

Vapor retarder A material that restricts the flow (transmittance) of water vapor.

Vault A continuous, curved roof member.

Vaulted ceiling High ceiling that follows the shape of the roof structure. If the gypsum board is attached directly to the rafters in a wood frame building (with no attic space), such a ceiling is called a vaulted ceiling.

Veneer A thin layer of material over a backup component. See also *adhered veneer* and *anchored veneer*.

Vertical diaphragm Walls that serve to transfer lateral loads in a building to the foundation by interacting with horizontal diaphragms (floor and roof structures).

Vinyl Abbreviation for polyvinyl chloride, used in window frames, plumbing pipes, and so on; sheet vinyl used in floor tiles, siding, trim, and so on.

Visible transmittance A measure of the transmission of visible light through glass.

Vision glass Transparent glass used between the spandrel areas of a curtain wall.

Visual grading A method of grading lumber based on visual inspection of each piece by trained (graders) inspectors.

Vitreous Glasslike substance with zero vapor permeability.

VT See *visible transmittance*.

W

Waffle slab Also called a two-way joist floor or ribbed slab that has closely spaced ribs (beams) in both directions. See also *ribbed slab*.

Waler Horizontal member used to stiffen and support concrete formwork.

Wall anchor A steel fastener that connects a veneer wall to the backup wall.

Wallboard See *gypsum board*.

Wall cavity Air space between the veneer and the backup wall.

Waterproofing Liquid or sheet material applied to the exterior of a basement wall or floor to resist the intrusion of water under hydrostatic pressure, as distinct from dampproofing.

Waterstop A rubber or polymeric strip of material, used to seal joints between two concrete pours.

Water table The level below ground where the water pressure due to the water in the soil equals the atmospheric pressure; the level below ground to which water will fill an excavation.

Wavelength Distance between adjacent air pressure maxima (compression peaks) or adjacent minima (rarefaction crests) at a given point in time caused by sound.

Weatherstripping Strip of material (wood, metal, foam, etc.) applied to an exterior door or window, which allows the unit to open and close but prevents the passage of air and rainwater when it is in the closed position.

Web Transverse element in a concrete masonry unit; the vertical part of a steel wide-flange section; members in a steel truss between the top and bottom chords.

Weep hole A small opening in a veneer wall directly above the flashing to drain water.

Weld Method of attaching two steel members by heating them until they fuse together.

Welded-wire reinforcement (WWR) A prefabricated rectangular grid of steel wires spot-welded together at intersections, used as reinforcement in concrete slabs.

Wet glazing A semiliquid elastomeric sealant used to set glass in a frame. See also *dry glazing*.

White cement White portland cement, commonly used in architectural concrete, stucco, and terrazzo flooring.

Wind load Difference between inside and outside air pressures on a building component caused by the wind.

Wind uplift Upward pressure caused by wind on a building component, generally on the roof.

Wired glass Rolled glass sheet with embedded thin steel wire mesh, used in fire-rated glazed openings.

Wood flooring Solid or manufactured wood available in strips, planks, and tilelike units and used as a floor finish.

Wood light frame A structural frame assembly composed primarily of dimension lumber studs, floor joists, and roof rafters and panels of wood-based sheathing materials.

Workability Ease with which fresh concrete can be placed and compacted, roughly measured by a slump test; ease with which fresh masonry mortar or portland cement plaster can be troweled on.

Worked lumber Lumber that has been machined beyond surfacing to obtain a specific profile or cross section.

Wrought iron Iron-carbon alloy that is hammered into shape.

Wythe Vertical section of masonry that is 1 unit thick.

Y

Yield strength Maximum stress in steel before it experiences excessive deformation.

Z

Zero-slump concrete A stiff concrete that will not settle at all in a slump test, generally used in making concrete masonry units.

Zoning ordinance A document that describes regulations for the use of land in a particular jurisdiction.

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